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OCEANOGRAPHY OF THE NEARSHORE COASTAL WATERS OF THE PACIFIC NORTHWEST RELATING TO POSSIBLE POLLUTION

VOLUME I

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SUMMARY AND CONCLUSIONS

1. The coast of the Pacific Northwest may be characterized as a series of steep, often unstable cliffs interspersed between broad sandy beaches. Rocky headlands and outcroppings are common, but the surface sediments of the nearshore zone are primarily sand. The shelf off Washington slopes more gently than that off Oregon and Northern California. No canyons or troughs extend into the nearshore zone and there is relatively little seismic activity compared to the remainder of the Pacific coast.

2. Maximum runoff from the major rivers of the area (excluding the Columbia) occurs in winter and spring as a result of heavy seasonal rainfall. Discharge of the Columbia River is greatest in June coinciding with runoff of snowmelt in Canada. Only the Columbia River appears to appreciably modify Pacific Ocean coastal waters.

3. Coastal winds are largely determined by the geographic position and intensity of the North Pacific high and the Aleutian low pressure areas. In the winter high velocity winds resulting from gales usually blow from the south or southwest. More often the winter winds prevail from the east. In spring the winds shift clockwise and by summer are predominantly from the northwest and west. In all seasons the coastal mountains tend to deflect the winds along the trend of the coast.

4. With few exceptions time series of temperature-salinity data are available only from intertidal stations or from lightships. Few measurements have been made in the area from shore to 10 km offshore. Surface temperatures range from an average summer high of 17.7°C to an average winter low of 7.6°C. Summer temperatures, which are influenced by upwelling, average about 5°C warmer than winter values. The Columbia River plume reduces surface salinity in nearshore waters off Washington in the winter. Upwelling tends to increase the salinities of nearshore waters in summer.

5. A heat budget may be used to describe the exchange of energy between the ocean and the atmosphere. Net heat exchanged

from year to year may vary considerably as the result of fluctuations in cloud cover, sea surface temperature, upwelling, and evaporation.

6. The wave climate of the Pacific Northwest coastal region has largely been determined by hindcasting based on climatological data. The predominant wave direction throughout the year is from the west to northwest. Waves with greatest heights and longest periods occur in the winter. Highest waves come from the southsoutheast to southwest sector. Periods of calms occur about equally in all seasons.

7. Coastal surface currents respond primarily to the local wind regime and thus can be expected to flow northward in winter and southward in summer. However, headlands, reefs, and irregularities in bottom contours produce complex series of interacting eddies which have received virtually no attention in the nearshore zone. Despite the lack of current measurements in this area, it is the nearshore surface circulation which will determine the distributions of contaminants released into the region.

8. Field studies of condenser cooling discharges from coastal power generating plants indicate that the physical effects are localized. The thermal plume usually takes the form of a surface lens about 2 to 4 m thick. The maximum distance warmed water has been observed from a coastal outfall is roughly 4 km.

9. Numerical models describing the dispersion of heated effluents from surface and subsurface outfalls may be useful in predicting the distributions of contaminants in the nearshore region. Although a number of simplifying assumptions are necessary and large capacity computers are required, such models offer promise for the solution of complex dispersion problems. Hydraulic models also may prove invaluable in the solution of various difficult problems.

10. Carbon dioxide concentrations and pH in seawater are closely related. High concentrations of CO_2 (to 525 parts per million) in the nearshore zone may result from upwelling. Uptake of CO_2 by photosynthetic organisms may reduce its concentration to as low as 155 parts per million. Surface pH values are generally near 8.1.

11. Dissolved oxygen concentrations in the nearshore zone from surface to 20 m is usually homogeneous from October to April. During May to September dissolved oxygen values at 20 m are more strongly influenced by upwelling than at the surface. In the absence of upwelling, representative nutrient concentrations in surface waters are: PO_4... 0.7 µg-atom/l; NO_3... 5 µg-atom/l; SiO_2... 10 µg-atom/l.

12. Pulp and paper mill effluents introduced into Pacific Northwest coastal waters may differ widely in their chemical characteristics. For this reason, the ecological effect of each outfall must be individually evaluated.

13. Relatively few measurements of the concentrations of toxic metals have been carried out in nearshore waters. Even less is known regarding physical and chemical forms of the metals. Apart from planktonic organisms, which may concentrate them greatly, metals may be lost from seawater by sorption, flocculation, ion exchange, precipitation, and co-precipitation.

14. Radionuclides in Pacific Northwest marine waters may be naturally-occurring, fission fragments from fallout of nuclear weapons tests, or neutron induced from weapons or from the Hanford plutonium production reactors on the Columbia River. Radioactivity from Hanford has drastically decreased in recent years with the serial shutdown of the plutonium production reactors. Atmospheric nuclear tests by France and Mainland China continue to cause fallout radioactivity in the coastal zone.

15. Concentrations of chlorinated hydrocarbons, used in forestry and agriculture in the Pacific Northwest, are generally low in marine organisms. Chlorine, which is sometimes used in water cooling systems as an antifouling agent, may have harmful short-term effects on planktonic organisms.

16. By far, the largest body of information on plants and animals of the outer coastal region is taxonomic. Relatively little is known regarding the ecological requirements of most species.

17. Some temperature data are available for 129 species of the more than four thousand organisms known from the Pacific Northwest coast. For most this amounts to a single temperature recorded at the time of collection. Temperature optima, ranges, and lethal limits are seldom known for more than one or a few life history stages, usually the adult.

18. Detailed biological information, such as life history, feeding habits, predators, and population dynamics, is most often available for fishes and invertebrates of direct commercial value to man. Comprehensive summaries of biological data for twenty selected species (or species groups) are included in Chapter 20. In addition, an annotated checklist including more than 750 plant species and 3,600 animal species is appended.

19. To begin to understand the nearshore coastal region it is necessary to view it as a system of interacting physical, chemical, and biological components. Contaminants, such as toxic chemicals or heated water, can be thought of as added environmental stresses which may alter the ecosystem drastically.

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A number of students helped with this research and their names have been included as authors in the sections where they contributed.

Finally our special thanks to Mrs. Suelynn Williams who typed the entire report.

Chapter 1. INTRODUCTION

The major problem facing mankind today is control of his rapidly increasing number and his rapidly increasing appetite for energy and raw materials. Since no politically or socially acceptable solutions have yet been found, it behooves us to prepare for expected population growth in a way which will compromise neither the quality of human life nor the quality of our environment.

One of the critical problems stemming from a population growth rate of greater than one percent per year is the unprecedented demand for electrical power. Power consumption is increasing by ten percent annually. The demands of the Pacific Northwest are presently met by a hydroelectric system which has already been developed to approximately one-half of its ultimate capacity. Expansion of the hydro-power system is essentially limited to the addition of generators to existing powerhouses. Future power demands will be met by the addition of thermal power plants to the hydroelectric system and are expected in 30 years to replace the latter as the source of basic power. The large number of projected power plants (approximately 30 of 1,000 megawatts or more capacity) carries with it the inherent threat of thermal additions to the environment.

The new thermal plants will either be fossil fueled or nuclear fueled. Initially, several of the new thermal plants may be fossil fueled, but the general lack of coal, oil, and gas in the Pacific Northwest and the expense of transporting fuels from other regions will limit their expansion. In addition to fuel limitations, there are the problems of air quality protection involving sulfur dioxide and particulate matter. Since these problems are seldom critical with nuclear fueled plants, it appears that nuclear powered steam electric plants will be the most probable source of new power for the Pacific Northwest.

The location of future power plants will be determined by both economic and environmental factors. Thermal power plants inherently waste large amounts of heat to the environment. Inland siting is often hampered by a lack of economically feasible sites for cooling ponds or lakes. Placement on rivers will decrease out of consideration of the important cold water fisheries in the Pacific Northwest and a lack of rivers with large year-round discharges. The biological importance of most estuaries and their limited flushing characteristics makes them undesirable sites. In addition, water quality in estuaries is highly variable. However, open coastal sites have the advantage of access to large volumes of water for cooling and dispersion, resulting in a potentially greater capacity for assimilation of industrial effluent without significant environmental damage. Coastal sites have therefore been earmarked as probable locations for a significant portion of the future power expansion in the Pacific Northwest. The advantages that make coastal siting of power plants favorable also pertain to other potential uses such as discharges of municipal and industrial wastes, pulp mill effluents, and offshore mining residues. The ocean, however, cannot be considered as an inexhaustible sink into which man can continuously dump his wastes. A balance must be achieved between the input of waste material and the ability of the ocean to assimilate it. Irreparable damage may result if this balance is not achieved.

To answer the environmental questions posed by use of the nearshore area for industrial outfalls, a coastal pollution group was formed within the Departments of Oceanography and Civil Engineering, Oregon State University. Supported by a grant from the Federal Water Quality Administration, this group has been charged to collect, organize, and analyze all oceanographic data which would aid in the evaluation of sites for industrial outfalls on the open coast of the Pacific Northwest. As a first step, a survey of the literature was needed to determine our present knowledge of this region and to help establish priorities for future research.

The area of concern in this literature survey is the nearshore coastal zone extending seaward 10 kilometers from the shoreline from Cape Mendocino in Northern California to Cape Flattery, Washington (Figure 1-1). Data relevant to the physical oceanography, geology, meteorology, chemistry, radioecology, and biology of this area were sought. Primary sources of data were the published literature, university theses, and unpublished data obtained directly from research laboratories. Detailed information concerning sources of data is presented in each chapter. Subject areas not researched are also indicated, as are data which, upon critical analysis, were found to be unsuitable for inclusion.

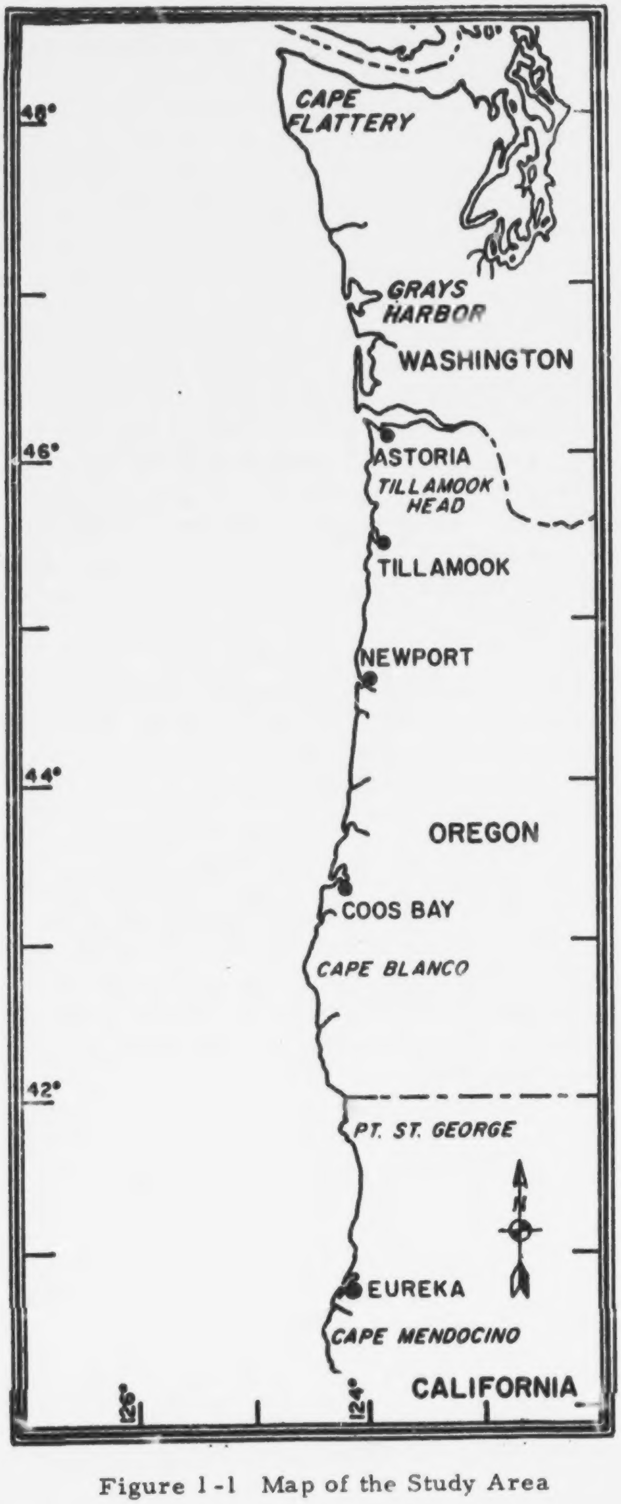

Figure 1-1 Map of the Study Area

This report, the final product of the project, represents the intensive cooperative efforts of physical oceanographers, chemists, geologists, biologists, and ocean engineers. The large volume of information collected has made it necessary to assemble the data in two volumes. Volume 1 is an analysis and detailed discussion of the collected information and contains a comprehensive bibliography of the literature pertaining to the nearshore regions of the Pacific Northwest. References are listed by author and bibliographic number. Part I of Volume 1 presents a discussion of the physical and geological factors which are known for the region of study. Part II summarizes the knowledge of the chemistry and radiochemistry of the region, and Part III considers the biological aspects with emphasis on temperature relations and attempts to establish some preliminary priorities. Part IV is an attempt to describe the coastal ecosystem by integrating the physical, chemical, geological, and biological information into a general overview. Volume 2 contains the appendices. Most of the physical and chemical data were suitable for inclusion in Volume 1, while it was necessary to include much of the biological information in the species checklist in the appendices.

The senior authors assume responsibility for the entire work, but since many individuals cooperated in this review, the names of the persons who worked on each section are included as chapter or subchapter authors. Without their able and conscientious assistance this task could not have been completed.

This report, then, is primarily a reference from which available information for this region can be abstracted on a regional or site basis. Information can also be obtained on physical parameters or on biological or chemical species or on any combination thereof. Perhaps more important than the presentation and summary of the available information is the indication of what information is not known or is not available.

PART I. PHYSICAL AND GEOLOGICAL ASPECTS

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Chapter 2. NAUTICAL CHARTS OF THE PACIFIC NORTHWEST COAST

by Burton W. Adams

The following Coast and Geodetic Survey Charts pertain to the area covered by this report. They may be purchased from the Director, Coast and Geodetic Survey, Environmental Services Admininstration, Rockville, Maryland 20852 or Officer in Charge U.S. Naval Oceanographic Distribution Office, Clearfield, Utah. These charts are listed in two general catalogs: (1) Nautical Chart Catalog No. 2 (1211) of the U.S. Coast and Geodetic Survey, and (2) Catalog of Nautical Charts and Publications, No. 1-N Region 0 (1216). Locations of regions described in this report are indicated on Figures 2-1 and 2-2.

AREA	CHARTS #	
A. San Francisco to Cape Flattery	C.&G.S.	5052
1. Monterey Bay to Coos Bay	"	5021
a. Pt. Arena to Trinidad Head	"	5602
(1) Cape Mendocino & Vicinity	"	5795
(2) Humbolt Bay	"	5832
(3) Trinidad Harbor	"	5846
b. Trinidad Head to Cape Blanco	"	5702
(1) St. George Reef & Cresent City	"	5895
(2) Pyramid Pt. to Cape Sebastian	"	5896
(3) Cape Sebastian to Humbug Mt.	"	5951
(4) Port Orford to Cape Blanco	"	5952
2. Cape Blanco to Cape Flattery	"	5022
a. Cape Blanco to Yaquina Head	"	5802
(1) Coquille River Entrance	"	5971
(2) Coos Bay	"	5984
(3) Umpqua River to Reedsport	"	6004
(4) Siuslaw River	"	6023
(5) Yaquina Bay & River	"	6055
(6) Approachs to Yaquina Bay	"	6056
b. Yaquina Head to Columbia River	"	5902
(1) Tillamook Bay	"	6112
(2) Nehalem River	"	6122
(3) Columbia River to Harrington Pt.	"	6151

AREA	CHARTS #	
c. Columbia River to Destruction Island	C. &G. S.	6002
(1) Willapa Bay	"	6185
(2) Grays Harbor	"	6195
d. Destruction Island to Amphitrite Pt. (Vancouver Is.)	"	6102
(1) Cape Flattery	"	6265

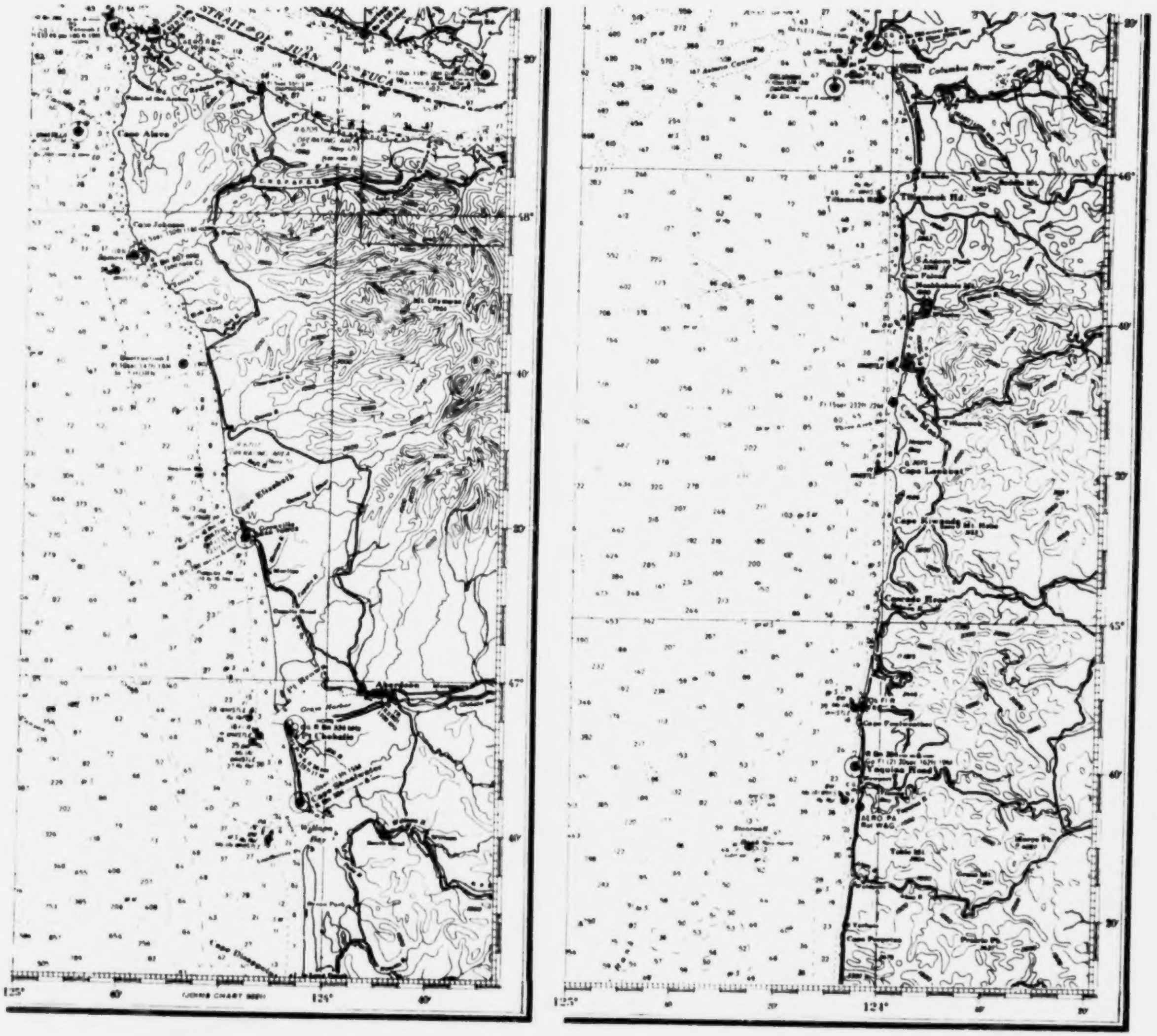

Figure 2-1. Pacific Northwest Coast. Cape Flattery, Wash. to Cape Perpetua, Ore.

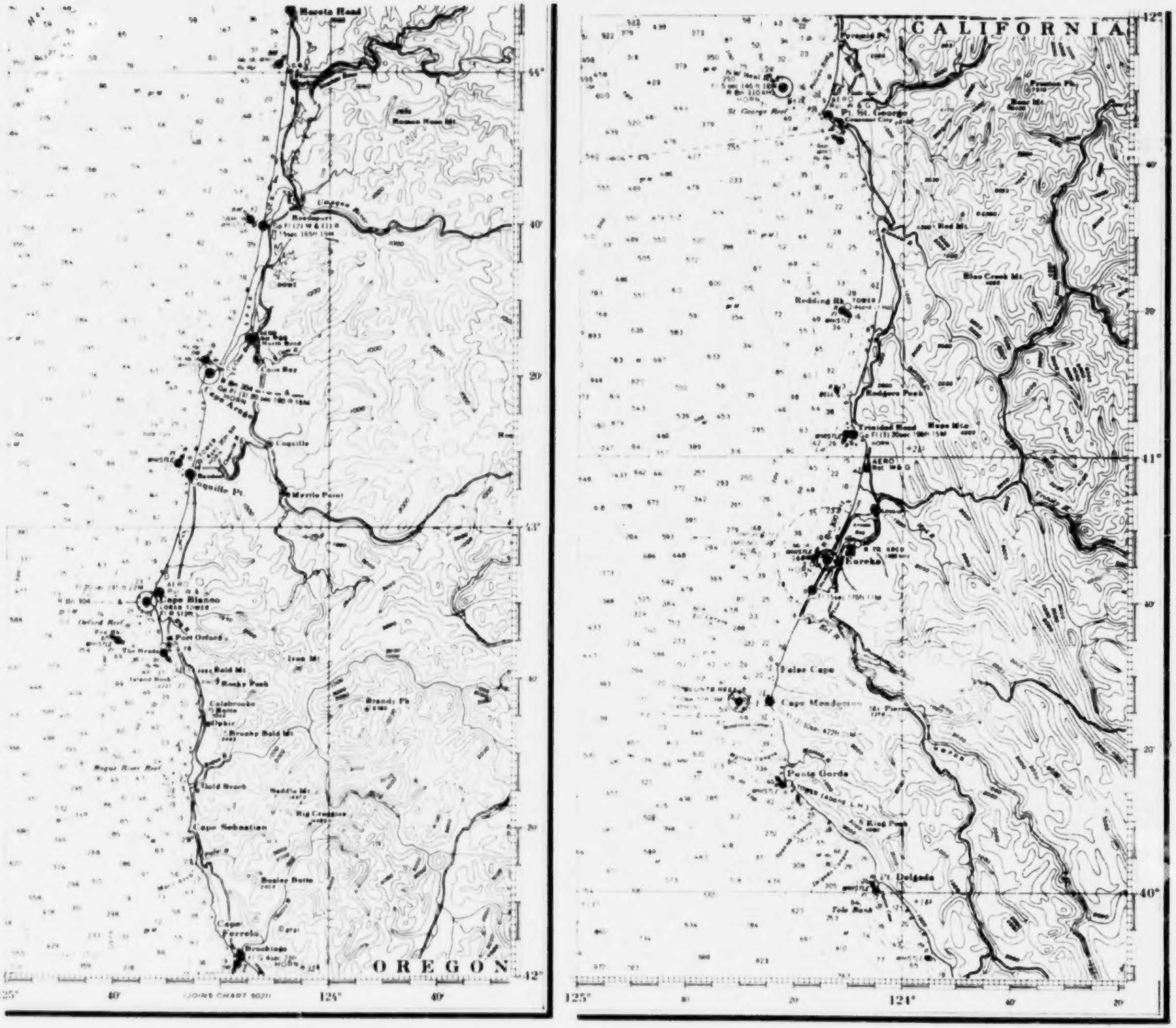

Figure 2-2. Pacific Northwest Coast. Heceta Head, Ore. to Pt. Delgada, Calif.

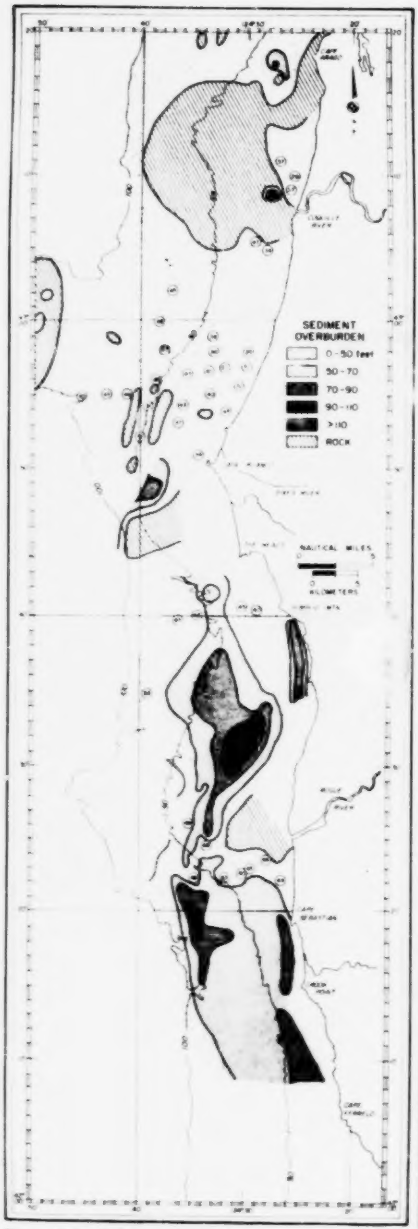

Figure 3-2. Sediment overburden. Numbers in circles indicate exact sediment thickness when measurable for the 0-50 foot interval. Contours in fathoms (from Kulm, 1730).

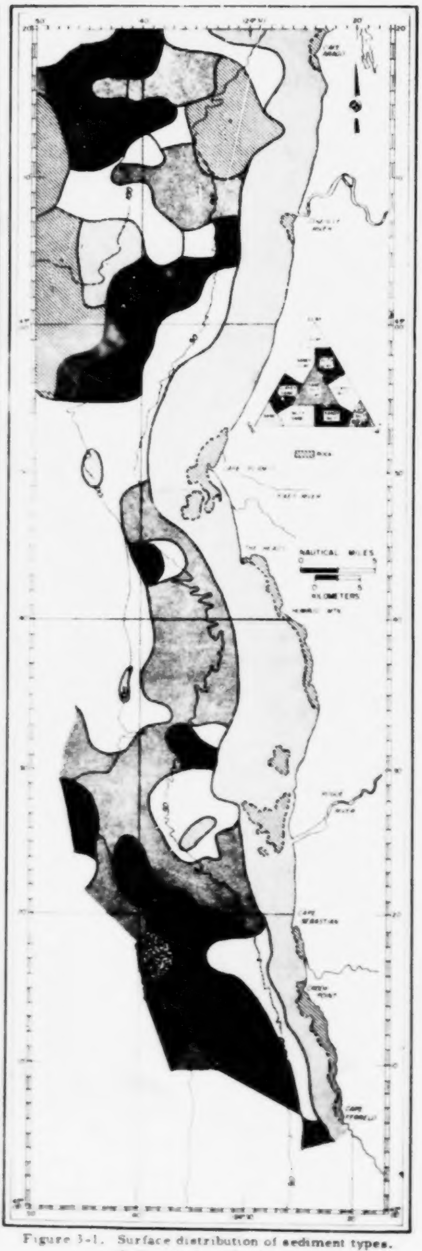

Figure 3-1. Surface distribution of sediment types. Sediment classification according to Shepard (1954). Contours in fathoms (from Kulm, 1730).

Chapter 3. GEOLOGY

by Robert H. Bourke, J. Paul Dauphine, and Burton W. Adams

Geology and Geomorphology

The geology of the nearshore region of the Pacific Northwest has not been studied in much detail. Inference must be drawn from the larger volume of geologic data gathered along coasts and beaches and from the marine surveys which have generally been conducted farther offshore than 2 to 3 miles. The geology of the Pacific Coast was discussed by Palmer (1741); the west coast of North America by Menard (1734); selected areas of the Pacific Northwest by Byrne (1714); and the coastal sand dunes of Oregon and Washington by Cooper (1716). A continuing study of the continental margin off Oregon is being conducted by the Department of Oceanography at Oregon State University. A detailed report for the southern Oregon coast has been compiled by Kulm (1730) and for the entire Oregon coast by Kulm and Fowler (1768). Major bathymetric features off the coasts of Oregon and Washington have been described by McManus (1765). Humboldt State College (1140) has documented the nearshore geology of the northern California region between Trinidad Head and the Eel River.

The coastal region of the Pacific Northwest may be described as erosional tectonic with uplifted submarine banks and coastal terraces. Numerous steep and often unstable cliffs are interspersed between sandy beaches. Rock outcrops are frequent in the vicinity of headlands and some river mouths (Figures 3-1 and 3-2). In southern Oregon typical areas of rock exposure are Cape Blanco, Cape Arago, and off the mouths of the Umpqua, Coquille and Rogue Rivers. Off the Washington coast, extensive gravel deposits have been found off Grays Harbor, the Quinault River, Ozette Lake, and Cape Flattery (Venkatarathnam, 1769). Site investigations for structures located on headlands or other cliff-like areas should consider possible slumping or slope failures (North and Byrne, 1739). General geologic features are shown and described on geological maps for Washington, Oregon, and California. Examples of these are:

(a) Geologic map of Oregon west of the 121st meridian (Peck, 1742)
(b) Geologic map of Washington (Huntting, et al., 1724) and
(c) Geology of Northern California (Bailey, 1759).

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Sediments

Surface sediments of the nearshore zone are primarily sands consisting of detrital quartz and feldspar. This sand zone extends from the shoreline out to a water depth of approximately 50 fathoms (300 feet) off the northern and central Oregon coast (Figure 3-3). South of the Umpqua River the sand forms a narrow belt along the coast in generally shallower water (30 fathoms or less) (Figure 3-1). Off the Washington coast the sand zone extends at least to a depth of 30 fathoms (1769). Off southern Oregon sediment thickness varies between zero and 90 feet (MacKay, 1733) (Figure 3-2). The onshore-offshore transport rate of sand is greatest during winter where, in areas subject to high wave attack, beaches may lose from 5 to 15 feet of sediment thickness. The longshore seasonal transport is generally to the north in winter and to the south in summer. Net longshore transport is believed to be north, but may vary with location (Kulm, et al., 1761). Ripples in the bottom sediment have been found at water depths of 80 meters in winter and 30 meters in summer (Neudeck, 1762). The transport and distribution of sediments from the Columbia River has been investigated by Ballard (1707) and Gross and Nelson (1722).

Sediment Motion

When a progressive wave advances into shoaling water, a depth is reached where the oscillatory fluid motion on the bottom is of sufficient magnitude to initiate sediment motion. This sediment motion may be significant to construction in the nearshore region.

Observations indicate that offshore gravity forces dominate over onshore hydrodynamic forces during the winter. Therefore, in the winter, beach sand is generally transported offshore. Under summer wave conditions the net onshore hydrodynamic force is greater than the offshore gravity force and the sand moves onshore.

Few observations have been made in the oceans to determine at what depth significant sand motion is initiated (see Inman, 1227) although considerable work has been done in laboratory wave tanks (Ippen, 1144). At present, the correlation between laboratory work and ocean observations is uncertain.

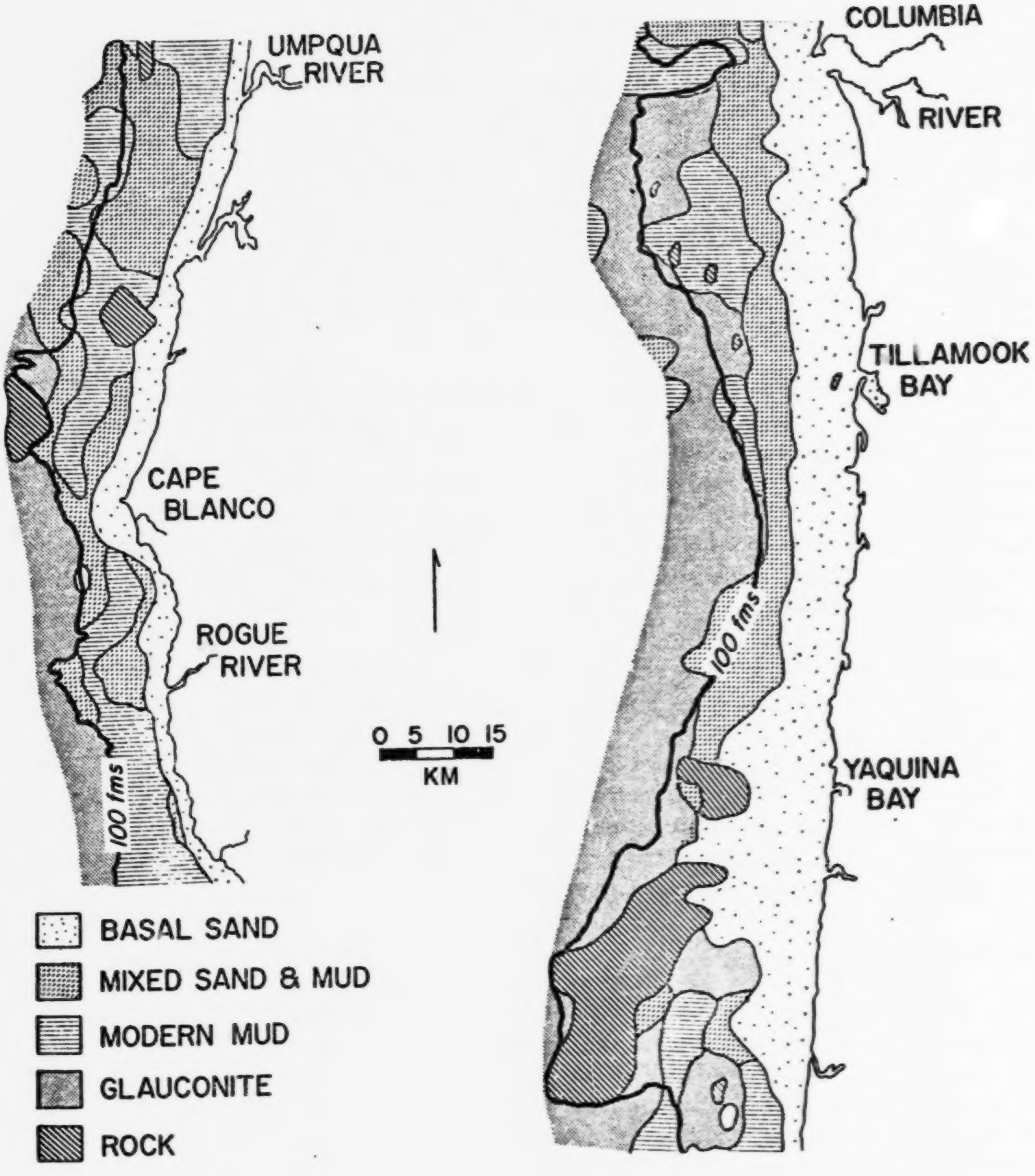


Figure 3-3. Sedimentary facies of the Oregon continental shelf (from Kulm and Fowler, 1768).

Inman (1227) indicated that the alignment of characteristic sediments parallel to the shoreline is caused by onshore/offshore sand movement, not littoral drift. Ippen and Eagleson (1144) have shown that the depth of established equilibrium motion (the deepest depth a characteristic sand particle remains in motion through a complete wave cycle) can be calculated for a characteristic beach slope, sand size, and wave. Figure 3-4 depicts depths of equilibrium motion for a beach with a slope of 0.015 and a sand diameter of 0.24 mm (D_{50}) for varying wave conditions.

A second approach to determine the depth at which sand movement is initiated for given wave conditions is to use small amplitude wave theory and Hjulstrom's curve (Figure 2.2 in 1121) for threshold velocities for different sand sizes. Figure 3-4 also shows solutions to the equation for threshold particle velocity on the bottom due to various wave conditions for a sand size of 0.24 mm (Glenne, 1228). The 0.24 mm sand size and 0.015 beach slope are representative of the Oregon coast.

Sorting of sediment sizes on the foreshore slope of a beach (landward of the breaker) is shown in Figure 3-5 from C. E. R. C. TR-4 (1121). The larger sized grains are associated with steeper beaches (a result of the higher orbital velocity of the water particles), but this relationship is also influenced by water level variability, wave exposure, and ground water level. Median grain size has been shown to be a satisfactory parameter for generally evaluating the transportability of littoral material.

Seismology

The coastal area of the Pacific Northwest is relatively aseismic compared to the remainder of the Pacific Coast. Hence, it may be considered a preferential siting area. The lack of major seismic activity is seen in the plot of tectonic flux (Figure 3-6)--an integration of earthquake intensity and number of quakes. Shear zones have been postulated through Cape Blanco and at Coquille Point, but these have not been active since post-Miocene (Dott, 1760).

Byerly (1710) and Menard (1734) have discussed earthquakes and faulting, respectively, along the Pacific Coast. Ryall, et al. (1770) have studied the seismicity, tectonism, and surface faulting of the Western United States. A discussion of Oregon earthquakes may be

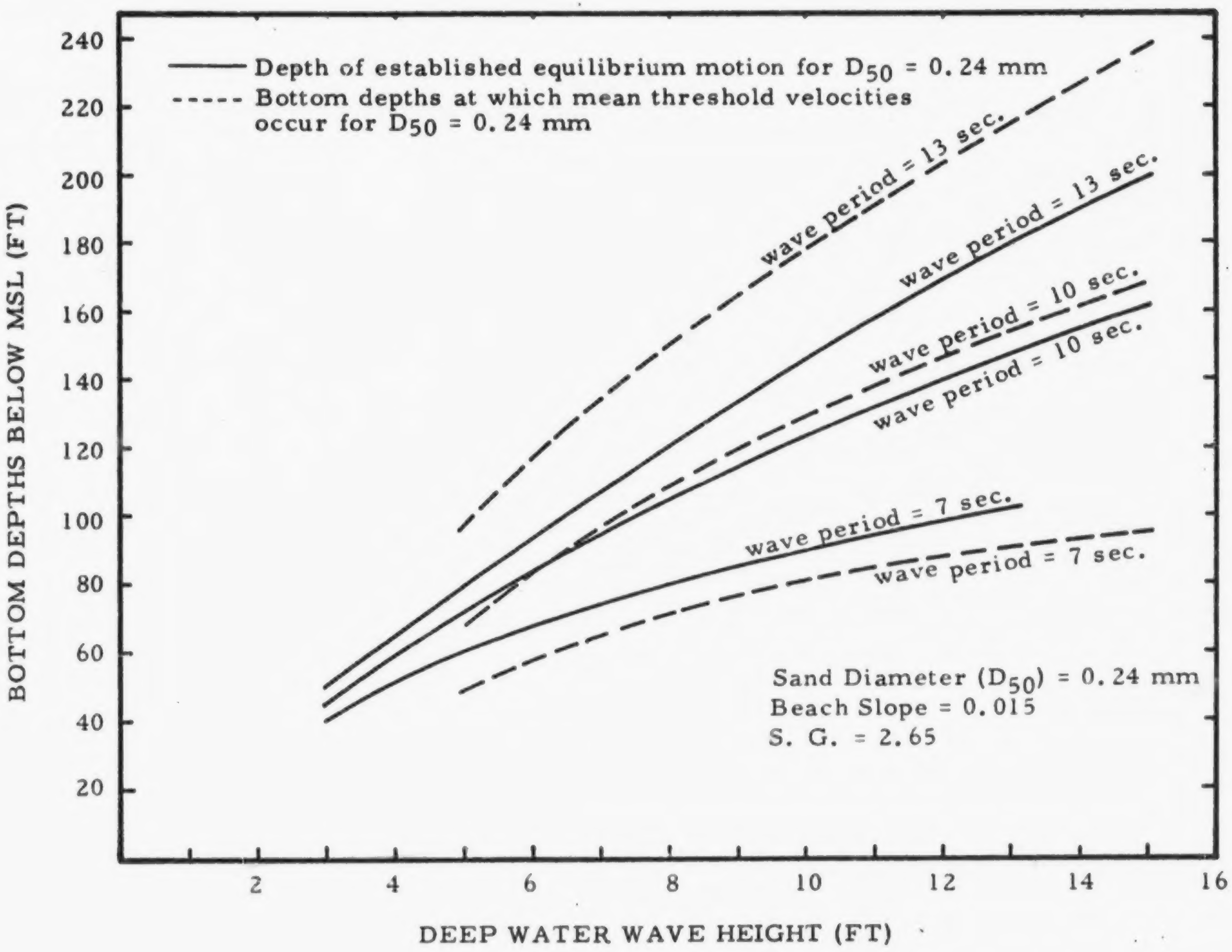


Figure 3-4. Movement of bottom sand due to waves.

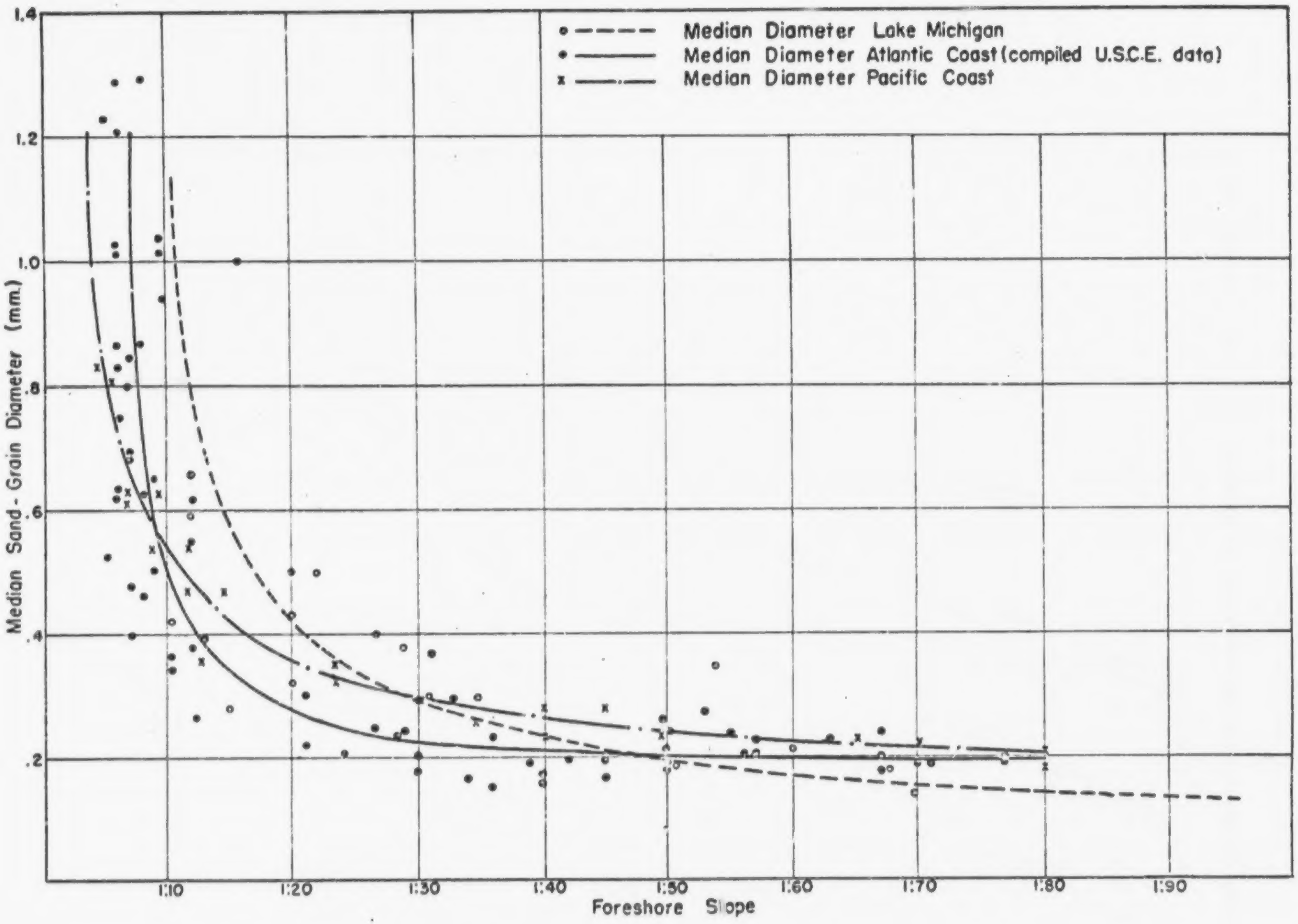


Figure 3-5. Relationship between grain size and foreshore slope (from C. E. R. C., TR-4, 1121).

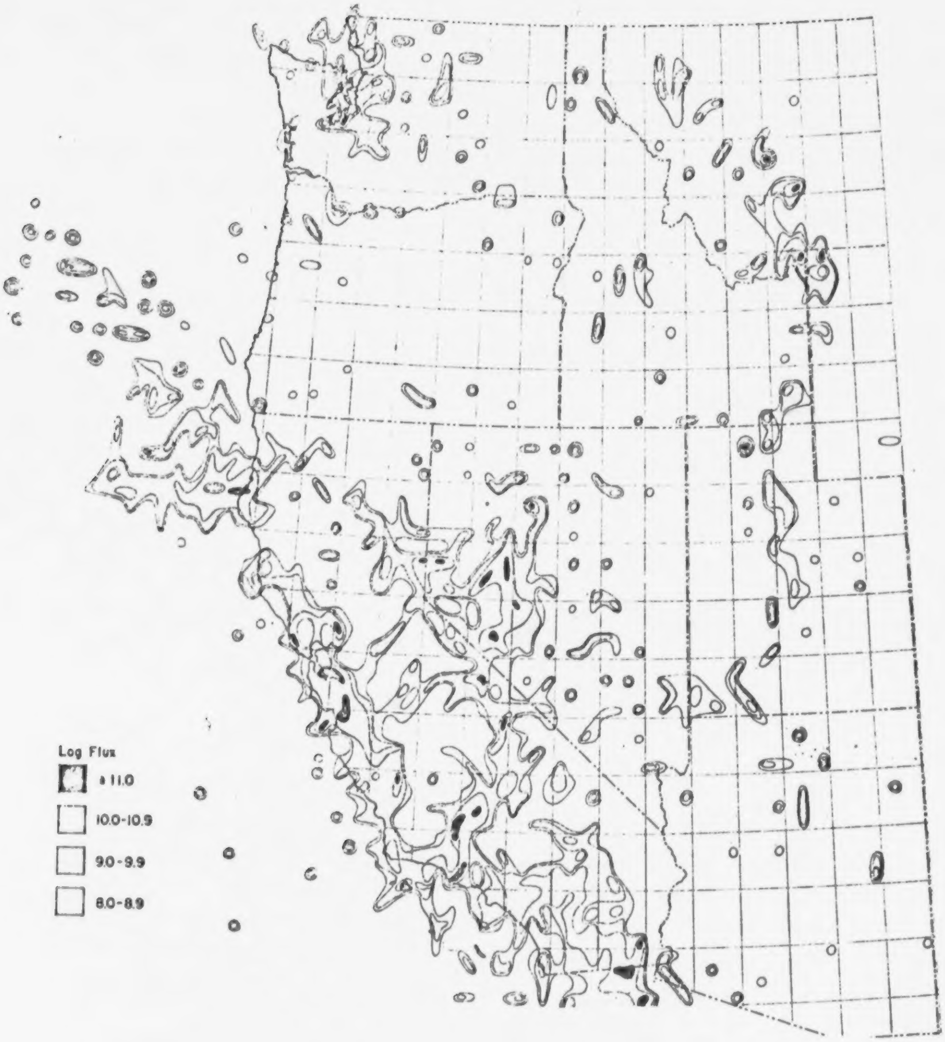


Figure 3-6. Map of tectonic flux for the Western United States (from Ryall, et al., 1770). Log flux indices represent combined intensity and frequency of quakes.

found in Berg and Baker (1708). Faults and shear zones of the continental shelf off Washington have been investigated by Grim and Bennett (1771).

Sources of Information

The following list of departments and bureaus are the major repositories of geologic data and information. These sources should be investigated for pertinent available data before commencing geologic surveys.

(a) State
  1. Department of Geology and Mineral Industries, State of Oregon
  2. Washington Department of Conservation, Division of Water Resources
  3. Washington Department of Conservation, Division of Mines and Geology
  4. California Division of Mines and Geology

(b)
  1. U. S. Geological Survey
  2. U. S. Bureau of Mines
  3. U. S. Bureau of Reclamation
  4. U. S. Coast and Geodetic Survey
  5. U. S. Army Corps of Engineers

Nearshore Topography

The nearshore topography of the study area can be illustrated by profiles of the bottom contour constructed at selected intervals along the coast from the shoreline out to a distance of three miles. Profiles or transects were drawn parallel to latitude lines and were located with reference to significant estuaries, population centers, broad flat beaches, headlands, and other coastal features.

The profiles shown in Figures 3-7 and 3-8 are of transects three nautical miles in length and are subdivided into three increments--shoreline to 0.5 mile, 0.5 to 1.5 miles, and 1.5 to 3.0 miles. The average bottom slope for each increment and the depth of water at 0.5, 1.5, and 3 miles offshore are shown.

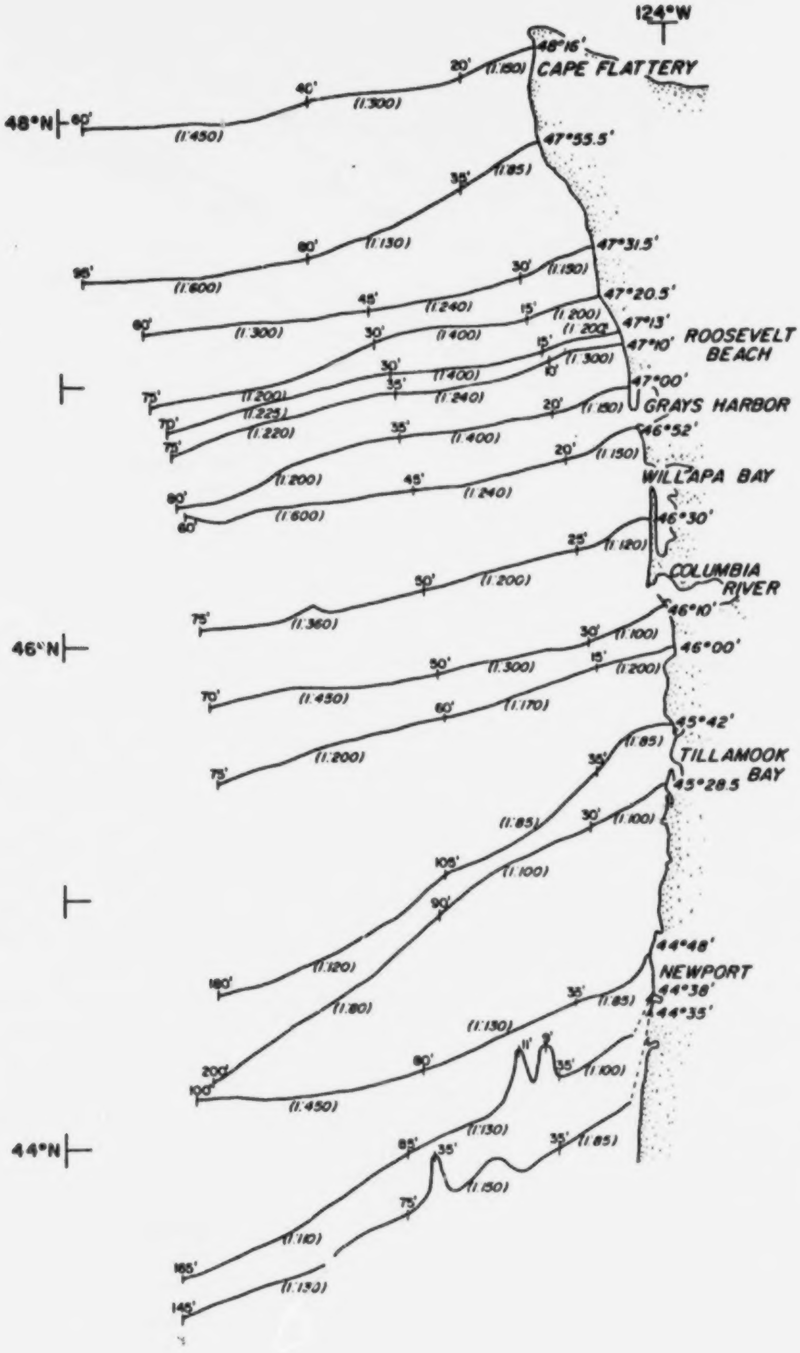


Figure 3-7. Bottom profiles and beach slopes for various locations in Washington and northern Oregon. Water depth is indicated at 1/2, 1 1/2, and 3 miles offshore.

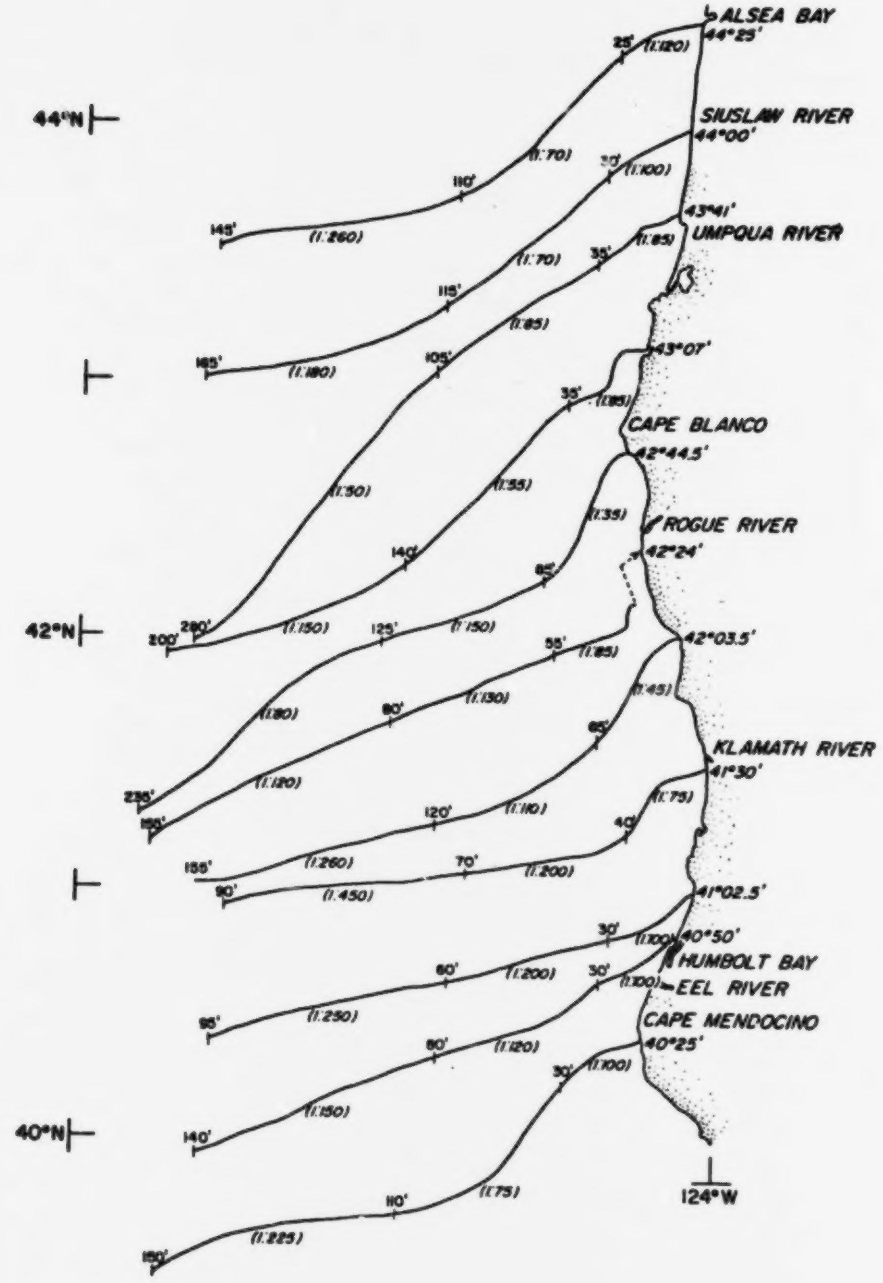


Figure 3-8. Bottom profiles and beach slopes for various locations in southern Oregon and northern California. Water depth is indicated at 1/2, 1 1/2, and 3 miles offshore.

The bottom slope of the first half mile increment is significantly greater than the slope farther offshore. From Cape Mendocino northward to Tillamook Head the slope is relatively steep ranging from 1:35 to 1:100 (1.75° to 0.5°); farther northward the slope is less, ranging from 1:100 to 1:200. At distances greater than one-half mile the slope is generally less, varying between 1:100 to 1:600 with the steeper slopes occurring south of Tillamook Head.

At a distance of one-half mile offshore the depth of water varies between 15 feet and 40 feet with a mean depth slightly greater than 30 feet. Three miles offshore in the northern portion the water depth rarely exceeds 100 feet. From Tillamook Head to the southern boundary the depth of water varies from 100 feet to 300 feet.

Several exceptions to the above mean conditions exist, notably around headlands. Here, offshore reefs and haystack rocks abound and bottom contours become quite irregular. In many of these cases high cliffs terminate abruptly at the water's edge eliminating the formation of any beach.

At Newport, Oregon, from Yaquina Head to approximately a mile south of the entrance jetties a submerged reef runs parallel to the coastline about a mile offshore. This reef alters the nearshore surface circulation pattern creating eddies of variable strength and direction. Similar situations will also exist in the proximity of other offshore rocky areas.

There are no known canyons or troughs that extend to within three miles of the coast. The heads of the Astoria and Eel River canyons terminate farther offshore, 15 miles and five miles, respectively.

Table 4-1. River discharge data for the Pacific Northwest.

River		Columbia	Chehalis	Umpqua	Rogue	Klamath	Eel	Coos	Coquille	Siuslaw
Drainage area for total basin - (mi^2)		259,000	2,012	4,560	5,160	15,800	3,630	415	1,058	773
Drainage area - (mi^2)		*	1,172	3,683	*	12,100	3,113	*	*	*
Percent of total basin gaged		*	88	80	*	78	86	*	*	*
Observation period		1953-67	1960-68	1953-67	1933-55	1958-67	1958-67	1930-61	1930-61	1937-63
Avg. monthly flow CFS	OCT	140,000	3,300	2,000	2,600	5,400	1,400	550	850	Estimated from precipitation records, stream not gaged
	NOV	192,000	11,200	7,300	6,600	11,100	5,000	2,400	3,550	
	DEC	246,000	15,900	16,600	11,900	24,500	17,000	4,500	6,600	
	JAN	263,000	19,800	18,300	16,200	25,900	18,000	5,300	8,050	
	FEB	266,000	13,000	16,100	15,600	30,600	19,500	5,500	8,250	
	MAR	239,000	10,700	13,200	12,300	24,600	12,700	4,000	6,050	
	APR	279,000	6,700	9,700	10,600	26,100	10,300	2,100	3,150	
	MAY	390,000	3,300	7,300	8,000	19,700	3,900	1,200	1,800	
	JUN	538,000	1,800	4,000	5,000	10,600	1,100	530	750	
	JUL	338,000	1,100	1,700	2,000	4,000	300	180	300	
	AUG	178,000	800	1,300	1,300	2,900	200	90	140	
	SEP	131,000	700	1,200	1,200	3,000	100	90	130	
Mean streamflow (cfs)		266,000	7,600	8,200	7,800	17,200	7,100	2,200	3,300	3,150
Avg. min. daily flow (cfs)		---	500	900	---	2,400	100	---	---	---
Avg. max. daily flow (cfs)		---	65,000	125,000	---	165,000	164,000	---	---	---

*Data extrapolated to river mouth.

Chapter 4. HYDROLOGY

by Bard Glenne and Burton W. Adams

Although the hydrology may effect many factors in the environment the discussion in this chapter will be limited to streamflow data. The effects of streamflow on temperature and salinity will be dealt with in Chapter 6 and on sediment transport in Chapters 3, 15, and 21.

Streamflow data for the nine major rivers discharging between Cape Flattery and Cape Mendocino are shown in Table 4-1. The data were taken from the records of the lowest gaging station on each river with the exception of the Siuslaw River which was estimated from precipitation records (1167) since no gaging stations were installed until 1967. Streamflow data for the Columbia, Rogue, Coos, and Coquille rivers have been extrapolated to the mouths of the rivers.

Streamflow data are available from the annual "Water Resources Data," published for each state by the U. S. Geological Survey (1213, 1214, 1215). The Northwest Water Resources Data Center (1163) publishes weekly and monthly streamflow summaries for selected stations in the Pacific Northwest. The Oregon State Water Resources Board has published river basin studies for the coastal basins of which the Rogue River (1165), North Coast (1223), Mid-Coast (1167), and South Coast (1168) basin studies were used.

The Columbia and Klamath Rivers show an annual bimodal flow discharge. This is a result of heavy autumn and winter precipitation west of the Cascade Range and spring snowmelt waters. Figure 4-1 shows the average monthly flow for the Columbia River showing the winter rainfall peak and the spring snowmelt peak.

The streamflow for the other rivers shows single peaks in winter due to heavy precipitation on the Coast Range during this season. Figure 4-2 depicts the streamflow for the Chehalis River which is representative of the flow pattern of these coastal rivers. A log-log plot of average coastal river streamflows versus river basin drainage area (Figure 4-3) permits estimation of streamflow for similar type rivers based upon a knowledge of the river drainage area.

To summarize, the discharge patterns of the coastal rivers emptying into the Pacific Ocean from Northern California, Oregon, and Washington show broad peaks during the winter and spring months. During summer and fall the discharge rates of these streams are much below their annual average (80 to 96 percent less).

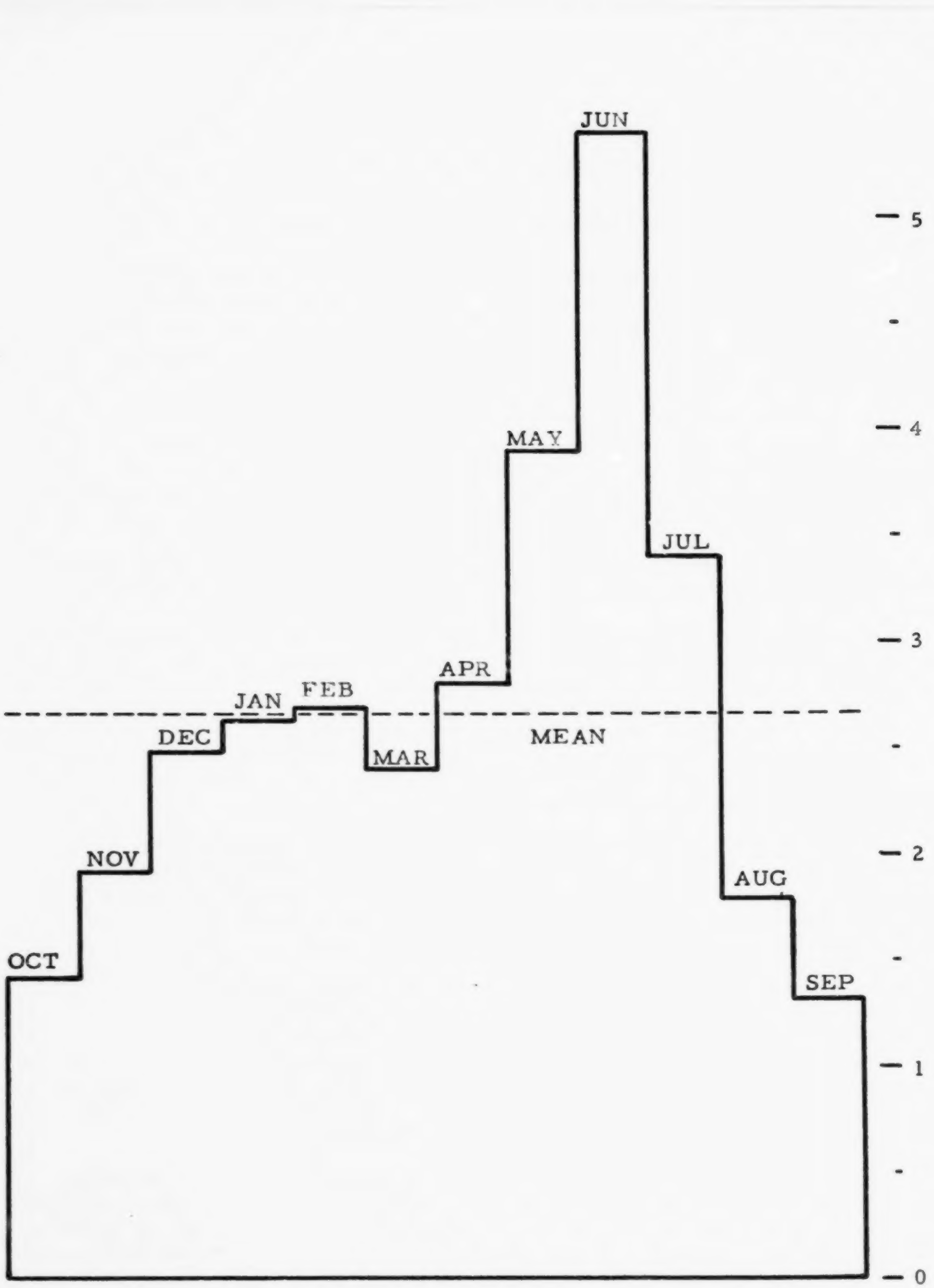


Figure 4-1. Mean monthly flow of the Columbia River extrapolated to the river mouth for 1953-1967. (CFS x 10^5)

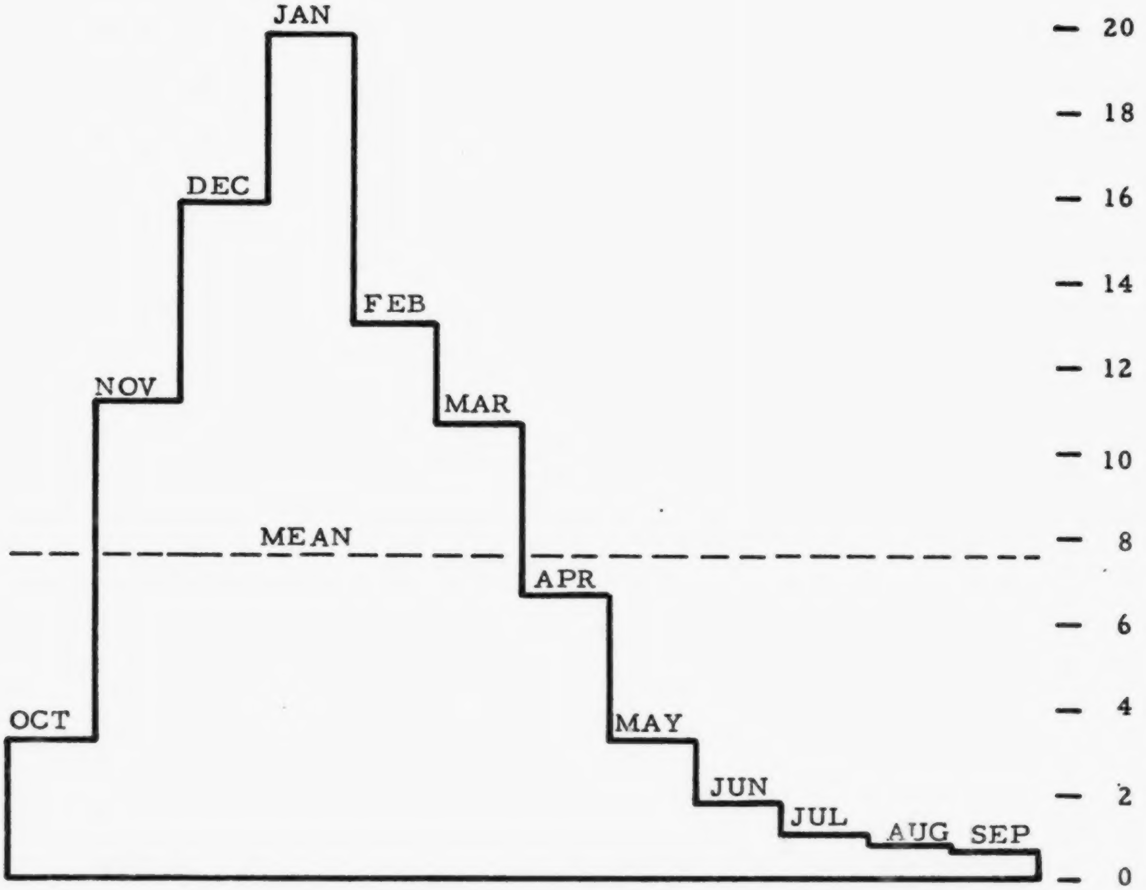


Figure 4-2. Combined mean flow of the Chehalis, Satsop, and Wynoochee Rivers measured at the lowest gaging station on each river for the period 1960-1968. (CFS x 10^3)

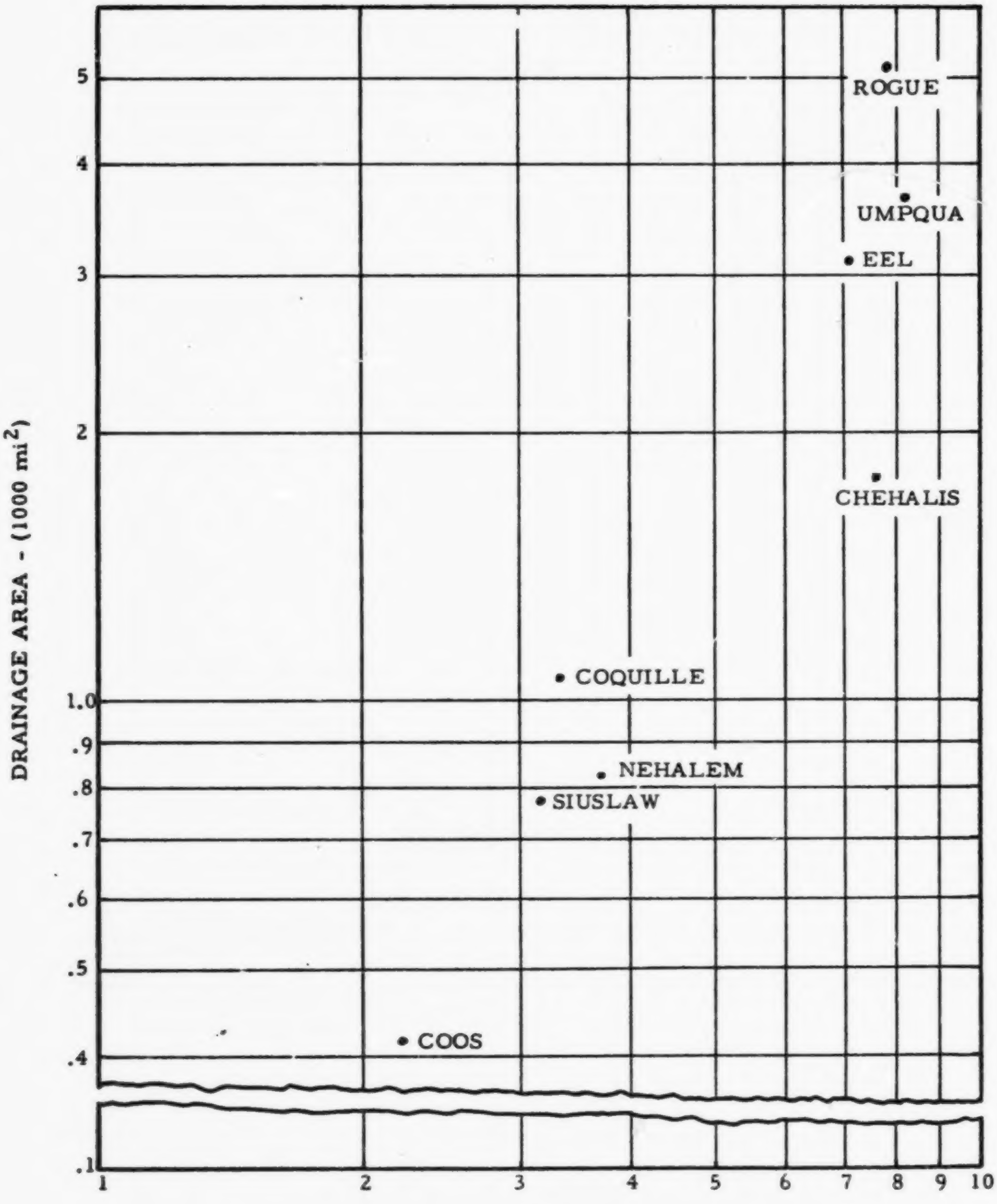


Figure 4-3. Average streamflow of Pacific Northwest coastal rivers versus river basin drainage area.

Chapter 5. WINDS

by Robert H. Bourke and Bard Glenne

General

The Washington, Oregon, and Northern California coasts are located approximately in the center of the zone of prevailing westerlies with local winds varying from northwest to southwest throughout most of the year.

The seasonal cycle ofwinds on the Pacific Northwest Coast is largely determined by the circulation about the North Pacific high pressure area and the Aleutian low pressure area. During summer the North Pacific high reaches its greatest development (approximately 1025 millibars) and is centered about 30-40°N and 150°W; the Aleutian low is weak during this period (Budinger, et al., 1113). The interaction of these pressure zones favors the development of summer winds generally from northwest to north over the nearshore and coastal areas of Oregon and Washington.

During winter the North Pacific high weakens and its center shifts about 10° southward while the Aleutian low intensifies (1113). The resulting winds, frequently of gale force, approach the Washington-Oregon coast from the southwest.

Extra-tropical cyclones occur most frequently in winter and generally approach the coast from a westerly direction (National Marine Consultants, 1159). Depending upon the location of the storm center as it impinges on the coast, the winds may be from northwest to southwest. These winds generate most of the large waves that reach the coast.

The barrier presented by the mountains of the Coast Range influence the general wind pattern, deflecting the winds so that they tend to align with the trend of the coast (Cooper, 1124). In regions where the mountains are low the deflecting effect is minimal and normal oceanic wind conditions prevail.

Table 5-1. Monthly averages of wind direction and scalar speed (mph) at selected shore stations.

Station a. Source of Data b. Bibliographic Reference No.	Period of Record		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Quillayute, Washington a. Weather Bureau b. (1207)	1966-1969	Average Direction Avg. Scalar Speed	SE 8.4	SE 7.3	SSE 7.7	S 7.5	SW 6.8	WSW 6.3	W 6.3	W 6.2	SSW 5.6	S 7.1	SE 7.1	SE 8.4
Moclips, Washington a. Weather Bureau b. (1155)	1937-1947	Average Direction	E	E	E	E	NW	NW	NW	NW	NW	E	E	E
Hoquiam, Washington a. Weather Bureau b. (1155)	1953-1958	Average Direction Avg. Scalar Speed	ESE 11.4	ESE 11.4	ESE 11.2	W 10.3	W 9.6	W 9.5	W 9.1	W 8.3	ESE 8.0	ESE 9.4	ESE 10.9	ESE 11.8
Lone Tree, Pt. Brown, Washington a. Weather Bureau b. (1193) and (1219)	12 years	Average Direction	SE	E	NW	NW	NW	NW	NW	NW	NW	NW	E	E
North Head, Cape Disappointment, Washington a. Weather Bureau b. (1193) and (1218)	44 years	Average Direction Avg. Scalar Speed	E 15.9	SE 14.6	SE 14.1	NW 13.8	NW 13.2	NW 12.8	N 12.0	N 11.2	N 11.7	SE 12.8	SE 15.5	E 16.2
Astoria, Oregon a. Weather Bureau b. (1206)	11 years	Average Direction Avg. Scalar Speed	E 8.9	ESE 8.7	SE 8.7	WNW 8.5	NW 8.2	NW 8.2	NW 8.5	NW 7.7	SE 7.2	SE 7.6	SE 8.5	ESE 8.8
Tillamook, Oregon a. Weather Bureau b. (1155)	1943-1945	Average Direction	S	SSW	NW	SSW	NW	NW	NW	NW	NW	S	S	S
Newport, Oregon a. Weather Bureau b. (1155)	1935-1942	Average Direction	E	E	E	E	NNW	NNW	NNW	NNW	NNW	S	E	E
Cape Arago Light Station, Oregon a. U.S. Army Corps of Engrs. b. (1197) and (1219)	1915-1925	Average Direction	SE	SW	SW	NW	NW	NW	NW	NW	NW	NW	SE	SE
North Bend, Oregon a. Weather Bureau b. (1155)	1950-1959	Average Direction Avg. Scalar Speed	SE 9.4	SE 8.4	SE 9.0	NNW 9.2	NNW 10.0	NNW 9.7	NNW 11.7	NNW 9.8	NNW 7.7	SE 6.8	SE 7.2	SE 8.3
Brookings, Oregon a. Weather Bureau b. (1155)	1937-1942	Average Direction	NE	NE	NE	NW	NW	NW	S	S	NW	N	NE	NE
Eureka, California a. Weather Bureau b. (1140)	-----	Average Direction Avg. Scalar Speed	SE 7.0	SE 7.2	N 7.6	N 8.0	N 7.9	N 7.4	NW 6.8	NW 5.7	N 5.5	N 5.6	SE 5.9	SE 6.4

Winds Measured from Shore Stations

Wind speed and direction have long been measured at various locations along the coast (prior to 1900 at some of the larger towns). However, very little of the data has been analyzed or published. For example, weather stations are found in most of the coastal towns, but data from only two locations are published: at Quillayute in northern Washington (U.S. Department of Commerce, 1207), and at Astoria, Oregon (U.S. Department of Commerce, 1208). For these two stations the resultant wind speed and direction (vector sum of all observations taken each month) and the mean scalar speed for each month have been published since 1967. Prior to 1967 the data listed were the prevailing wind direction, frequency, and the mean scalar speed.

At each of the U.S. Coast Guard Stations the climatological data are recorded every four hours. Only the immediate past year's and present year's logs are kept at the stations; the records for previous years are sent to the Coast Guard Archives, Washington, D.C. These records have not been machine punched nor analyzed and have not been used in this report.

In addition to the above two sources of wind data, the U.S. Army Corps of Engineers has completed wind analyses for several harbors and bays in the study area (1196-1201). Most of these reports are from data taken prior to 1930.

In March 1969 the Weather Facility at the Marine Science Center in Newport, Oregon, installed a recording anemometer on the end of the south jetty of Yaquina Bay. Data from this source should prove quite reliable since the location of the anemometer provides data relatively free of land effects.

Average wind conditions as measured at various coastal sites within the study area are presented in Tables 5-1 and 5-2. Wind roses for winter and summer conditions (January and July, respectively) for Oregon are shown in Figure 5-1.

Winds have been monitored at the Quillayute weather station since July 1966. Prior to July 1966 all meteorological observations were made at the weather station on Tatoosh Island. The wind pattern for the northern Washington coast differs from that along the southern Washington, Oregon, and northern California coasts in that at Quallayute summer winds are from the west, whereas, for the latter areas summer winds are consistently from the north or northwest.

Table 5-2. Frequency and velocity of winds at three stations on the Washington-Oregon coast

July and January

	North Head, Washington Lat. 46°18'			*Newport, Oregon Lat. 44°38' 1934–1942*			*North Bend, Oregon 43°25' 1937–1942*		
	Frequency		*Av. velocity*	*Frequency*		*Av. velocity*	*Frequency*		*Av. velocity*
	4 m.p.h. and over	*16 m.p.h. and over*	*m.p.h.*	*4 m.p.h. and over*	*16 m.p.h. and over*	*m.p.h.*	*4 m.p.h. and over*	*16 m.p.h. and over*	*m.p.h.*
July	*1930–1942*								
N.	781	410	15.4	389	135	11.9	351	130	12.6
N.-N.E.	15	3	8.4	6	...	4.9	36	2	7.8
N.E.	11	...	5.6	2	..	2.5	37	...	5.2
E.-N.E.	...	...	....	2	...	3.0	2	...	3.3
E.	10	...	5.5	34	...	3.0	6	...	3.1
E.-S.E.	1	...	10.0	11	...	3.8	2	...	3.5
S.E.	44	7	9.2	35	1	3.6	52	...	4.5
S.-S.E.	36	10	13.6	9	...	5.4	20	...	5.3
S.	269	114	14.7	60	5	6.4	24	...	4.3
S.-S.W.	39	14	13.4	48	1	7.9	19	...	7.1
S.W.	129	11	10.1	117	...	6.2	39	...	5.7
W.-S.W.	24	1	7.8	34	...	6.7	19	...	7.5
W.	127	9	8.1	55	...	4.7	16	...	4.8
W.-N.W.	20	2	9.0	27	..	5.6	12	1	7.6
N.W.	437	155	13.1	160	15	7.9	330	70	10.1
N.-N.W.	323	171	15.9	212	60	12.6	172	45	11.3
January	*1931–1942*								
N.	84	22	11.8	33	3	7.3	28	...	5.4
N.-N.E.	6	...	7.6	6	...	6.4	4	...	6.2
N.E.	61	2	6.0	17	...	5.7	52	1	6.1
E.-N.E.	6	3	9.1	97	...	7.2	5	...	6.0
E.	501	194	13.0	415	6	7.3	19	...	4.8
E.-S.E.	183	110	16.6	160	2	8.5	12	...	4.4
S.E.	383	152	14.3	235	2	6.7	614	5	7.2
S.-S.E.	36	23	19.2	25	4	10.5	149	2	7.3
S.	313	263	27.8	122	59	14.1	114	15	8.9
S.-S.W.	23	23	27.7	46	23	16.1	28	5	12.1
S.W.	125	87	19.9	75	20	11.2	93	23	11.2
W.-S.W.	6	4	15.1	28	10	13.1	7	1	9.9
W.	127	69	16.0	76	7	8.7	12	1	7.2
W.-N.W.	8	5	16.3	17	1	8.1	3	...	5.8
N.W.	118	68	16.8	32	5	9.5	66	9	8.9
N.-N.W.	13	9	18.8	6	...	9.7	11	...	5.[illegible]

(from Cooper, 1124)

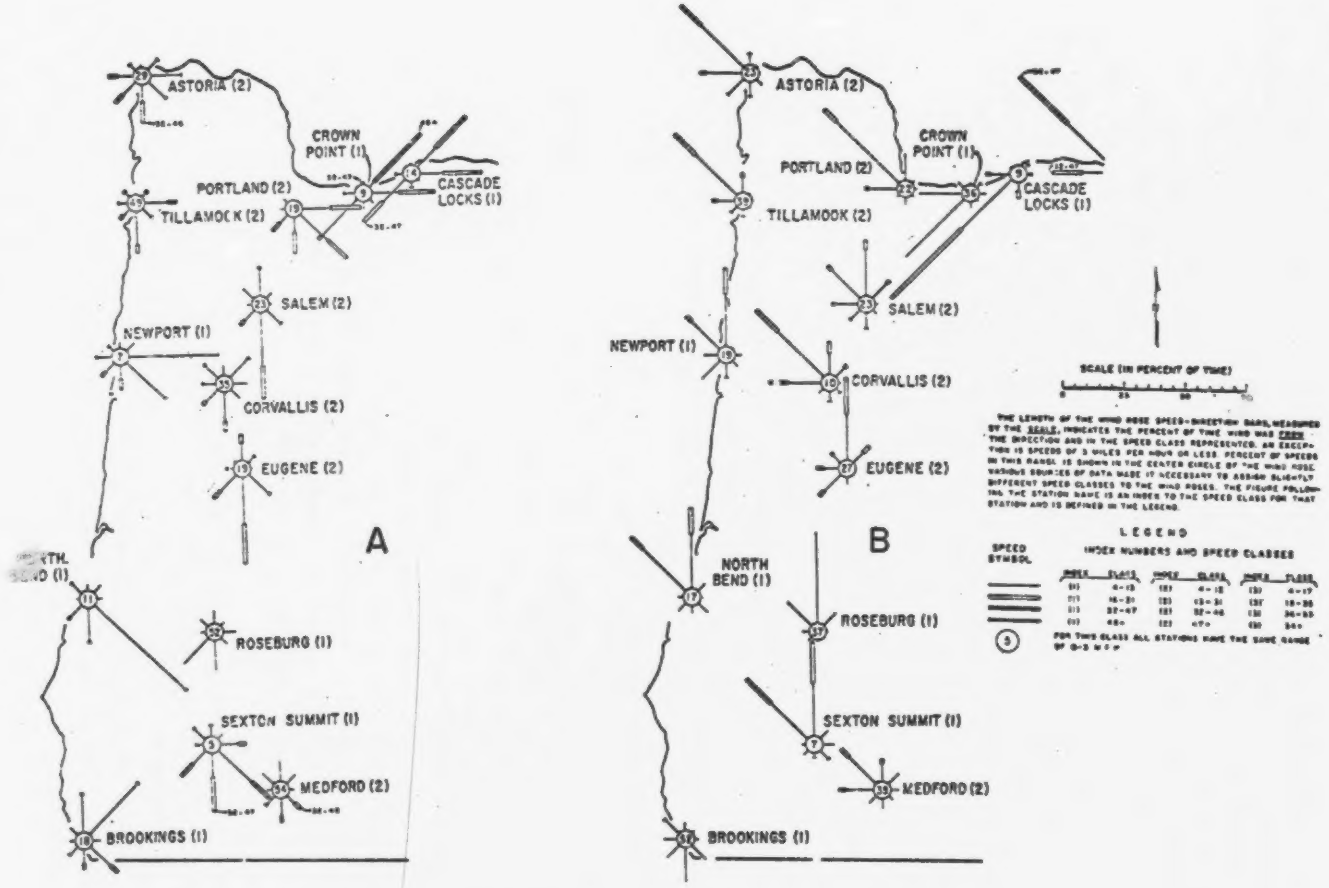

ASTORIA (2)
CROWN POINT (1)
PORTLAND (2)
CASCADE LOCKS (1)
TILLAMOOK (2)
SALEM (2)
NEWPORT (1)
CORVALLIS (2)
EUGENE (2)
A
NORTH BEND (1)
ROSEBURG (1)
SEXTON SUMMIT (1)
MEDFORD (2)
BROOKINGS (1)
B
SCALE (IN PERCENT OF TIME)
0
25
50
75
THE LENGTH OF THE WIND ROSE SPEED-DIRECTION BARS, MEASURED BY THE SCALE, INDICATES THE PERCENT OF TIME WIND WAS FROM THE DIRECTION AND IN THE SPEED CLASS REPRESENTED. AN EXCEPTION IS SPEEDS OF 3 MILES PER HOUR OR LESS. PERCENT OF SPEEDS IN THIS RANGE IS SHOWN IN THE CENTER CIRCLE OF THE WIND ROSE. VARIOUS SOURCES OF DATA MADE IT NECESSARY TO ASSIGN SLIGHTLY DIFFERENT SPEED CLASSES TO THE WIND ROSES. THE FIGURE FOLLOWING THE STATION NAME IS AN INDEX TO THE SPEED CLASS FOR THAT STATION AND IS DEFINED IN THE LEGEND.
LEGEND
SPEED SYMBOL
INDEX NUMBERS AND SPEED CLASSES
INDEX CLASS
(1) 4-15
(1) 16-31
(1) 32-47
(1) 48+
INDEX CLASS
(2) 4-12
(2) 13-31
(2) 32-46
(2) 47+
INDEX CLASS
(3) 4-17
(3) 18-35
(3) 36-53
(3) 54+
FOR THIS CLASS ALL STATIONS HAVE THE SAME RANGE OF 0-3 M P H

Figure 5-1. Wind roses for winter and summer conditions for western Oregon.
a. Wind roses for January.
b. Wind roses for July.
(from U. S. Dept. of Commerce-Weather Bureau, 1210)

For the three stations near the Columbia River--Lone Tree, North Head, and Astoria--summer winds are predominantly from the N-NW quadrant paralleling the coast; the highest velocity winds are also from this sector (Table 5-2). During winter the winds are predominantly offshore--from east or southeast. These winds are, however, of moderate speed. The higher velocity winds (16 mph or more, Table 5-2) arrive from the south or southwest, but do not occur as frequently as the moderate easterly winds. High velocity winds from the east also occur in this region during the winter as a result of the concentration of the wind stream in the Columbia River gorge (1124). In general, wind speeds are greater in winter than summer with the exception of the high velocity summer winds from the north.

Winds measured at Newport and Coos Bay, Oregon, and at Eureka, California, exhibit the similar pattern of north or northwest winds in summer and southeast winds in winter. The winds here tend to follow the general trend of the coastline. Spring and fall are transition seasons during which the wind swings from south to north and vice versa; the weather during these periods is usually clear.

Offshore Wind Observations

Observations of offshore winds taken near the vicinity of a marine outfall are one of the necessary parameters required to describe the distribution pattern of a surface pollutant. The winds not only blow the pollutant along the ocean surface, but create wind-driven currents which carry the "body" of the pollutant away from the source. Wind speeds measured at shore stations, e. g. , Weather Bureau and Coast Guard Stations, are generally not representative of conditions found one-half to five miles offshore due to the varying topography along the coast. Unfortunately, observations made one to five miles offshore are very few and widely scattered.

Wind speed and direction measured aboard merchant, naval, and research vessels in transit are deposited in the National Oceanographic Data Center (NODC). Analysis of these data to obtain average monthly wind conditions showed that the few observations taken within the study area were too widely distributed in space and time to be of any statistical value.

The geostrophic wind can be computed from twice-daily atmospheric pressure charts prepared by the U. S. Weather Bureau. Corrections can be applied to the geostrophic wind to obtain the approximate surface wind condition for a height of 10 meters above the sea surface. An analysis of offshore wind conditions using this method is described in a technical report of the Department of Oceanography of the University of Washington (Duxbury, et al., 1128).

Perhaps the most reliable and representative of actual surface wind conditions recorded are those measured from lightships stationed about five miles offshore. These data are stored at the National Weather Records Center in Asheville, N.C. If specifically requested, the data are machine punched and put on magnetic tape for future analysis.

On a broader scale, the Climatological and Oceanographic Atlas for Mariners, Volume II, North Pacific Ocean (U. S. Dept. of Commerce, 1209) shows monthly wind roses for a point located at 41°00'N, 126°00'W. Only general seasonal trends can be elicited from this Atlas.

In the future, valuable wind information will be provided by telemetry from buoys such as Oregon State University's Totem. These buoys should provide long and continuous records allowing statistical analysis of short-term fluctuations as well as long-term averages.

Since the early 1950's wind observations have been recorded every six hours from the three lightships located in the project area. These are the Blunts Reef Lightship off Cape Mendocino in northern California, the Columbia River Lightship, and the Umatilla Lightship off Cape Alava in northern Washington (Figure 5-2). The data analysis to obtain average monthly wind conditions was performed for this project by the National Weather Records Center. Table 5-3 lists by month the average resultant wind direction and speed, the average scalar speed and the number of observations during the period of record for each lightship. In addition, Appendix 1 is a listing of the above information for each year within the period of record.

Offshore winds in the northern section of the area (Umatilla Lightship data) shift from SSE in fall and winter to W in early summer and then reverse the cycle. This same pattern is observed in the central and southern sections except that during summer the winds continue their clockwise swing and arrive from the NW and N, respectively. This annual wind shift is also verified by Figure 5-3 which was derived from geostrophic calculations. These winds, measured

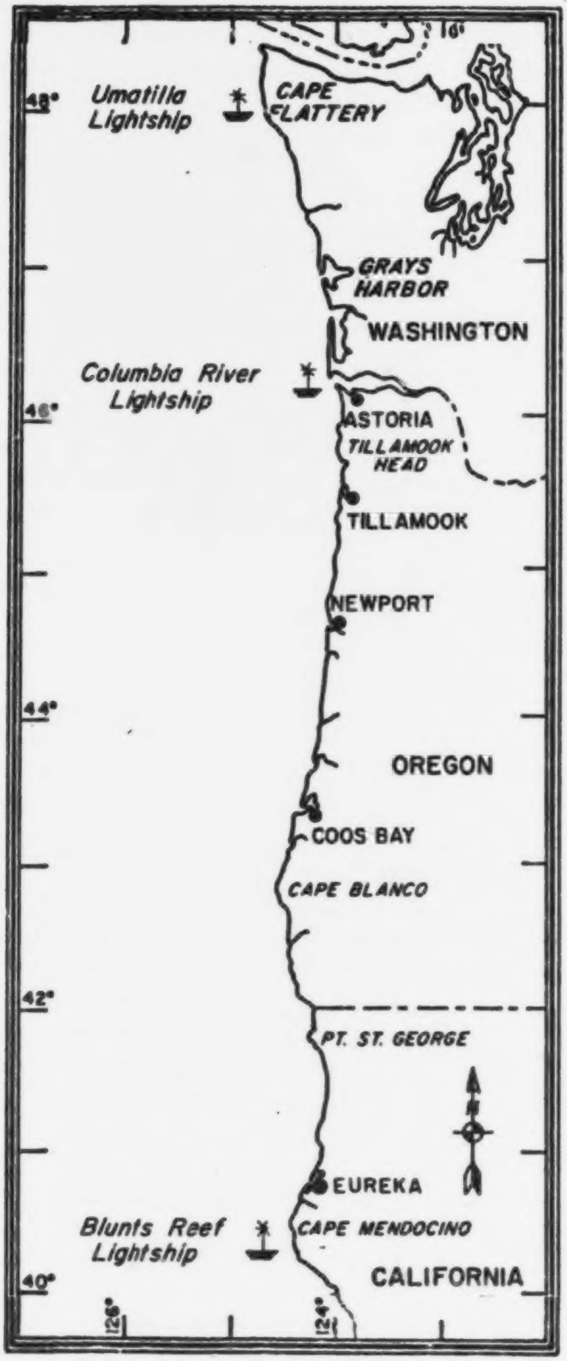


Figure 5-2. Location of lightships off the Pacific Northwest coast.

Table 5-3. **Resultant wind speed (knots) and direction by month measured from lightships off the Pacific Northwest coast.**

Blunts Reef Lightship
1954-1966 (13 yrs)

	Resultant Direction		Resultant Speed	Scalar Speed	Number Observations
Jan	131	SE	4	18	1609
Feb	091	E	2	19	1465
Mar	023	NNE	2	18	1591
Apr	357	N	8	18	1523
May	355	N	10	18	1481
June	351	N	12	15	1554
July	356	N	14	16	1491
Aug	359	N	13	16	1548
Sept	002	N	9	14	1536
Oct	015	NNE	5	13	1470
Nov	113	ESE	3	16	1554
Dec	134	SE	4	17	1594

Columbia River Lightship
1953-1966 (14 yrs)

	Resultant Direction		Resultant Speed	Scalar Speed	Number Observations
Jan	155	SSE	9	18	1715
Feb	174	S	6	16	1560
Mar	192	SSW	5	15	1727
Apr	233	SW	4	13	1546
May	279	W	4	12	1627
June	291	WNW	4	10	1680
July	317	NW	6	10	1613
Aug	305	NW	4	10	1732
Sept	298	WNW	1	11	1588
Oct	159	SSE	4	14	1512
Nov	157	SSE	6	17	1507
Dec	163	SSE	8	17	1608

Umatilla Lightship
1961-1965 (5 yrs)

	Resultant Direction		Resultant Speed	Scalar Speed	Number Observations
Jan	182	S	7	18	557
Feb	167	SSE	4	16	675
Mar	210	SW	3	14	693
Apr	208	SW	5	15	713
May	265	W	5	13	745
June	266	W	5	12	719
July	238	WSW	4	10	860
Aug	206	SW	2	7	925
Sept	179	S	2	8	900
Oct	167	SSE	8	13	923
Nov	161	SSE	9	16	898
Dec	168	SSE	9	17	930

5 miles off the coast, show that even at this distance offshore the influence of the continental topography is still marked.

Corrected Geostrophic Winds

Duxbury, Morse, and McGary (1128) have computed the resultant surface wind from atmospheric pressure charts for eight grid points shown in Figure 5-3. The geostrophic wind velocity aloft was determined and then corrected by rotating the wind vector 15° to the left of its downwind direction and reducing the speed by 30% to obtain a surface wind applicable to a standard height of 10 meters above the sea surface. These winds were then averaged by month for the period 1961-1963 for three offshore grid areas (Figure 5-3). Seasonal trends and latitudinal variations are readily apparent. Winter winds are predominantly from the southwest, while summer winds are northwest in the northern areas and from the north in the southern part. The wind direction changes quite smoothly over a 180° arc between summer and winter and back to summer. Resultant wind speeds during the autumn and spring transition periods are relatively low due to the wide variability in wind direction during these seasons.

Wind roses for each month, centered at the midpoint of the grid from which the wind values were determined, are shown in Figures 5-4 to 5-15. The percentage of each month the wind came from the direction indicated is represented by the length of the bar. The concentric circles indicate both 5-knot speed increments and monthly frequency of occurrence in 5% intervals. The small numbers indicate the frequency of occurrence within each 5-knot increment; the sum over any particular direction indicates the frequency with which the wind came from the direction shown. The bar graph associated with each rose shows the monthly frequency of wind speed in 5-knot increments without regard to direction. The increase in wind strength during winter followed by the decrease in strength in summer is readily observed for the northern and central areas. Winds in the southern area remain relatively strong in both summer and winter. The close agreement of the "corrected geostrophic winds" with those winds observed at the lightships substantiates earlier reports that geostrophic winds may be used in areas where actual wind observations are meager.

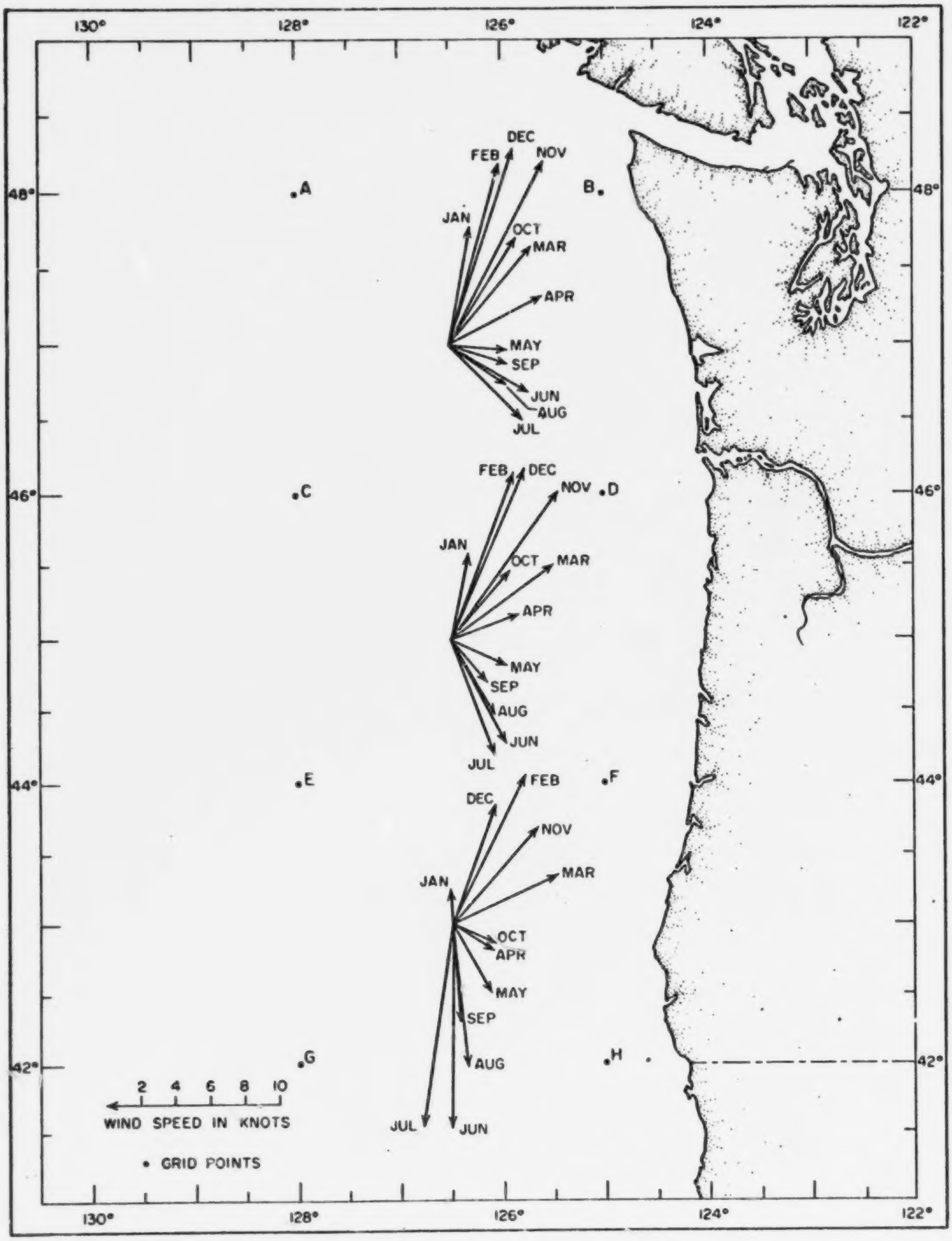


Figure 5-3. Average direction and velocity of monthly winds for 1961-1963.

(from Duxbury, et al., 1128)

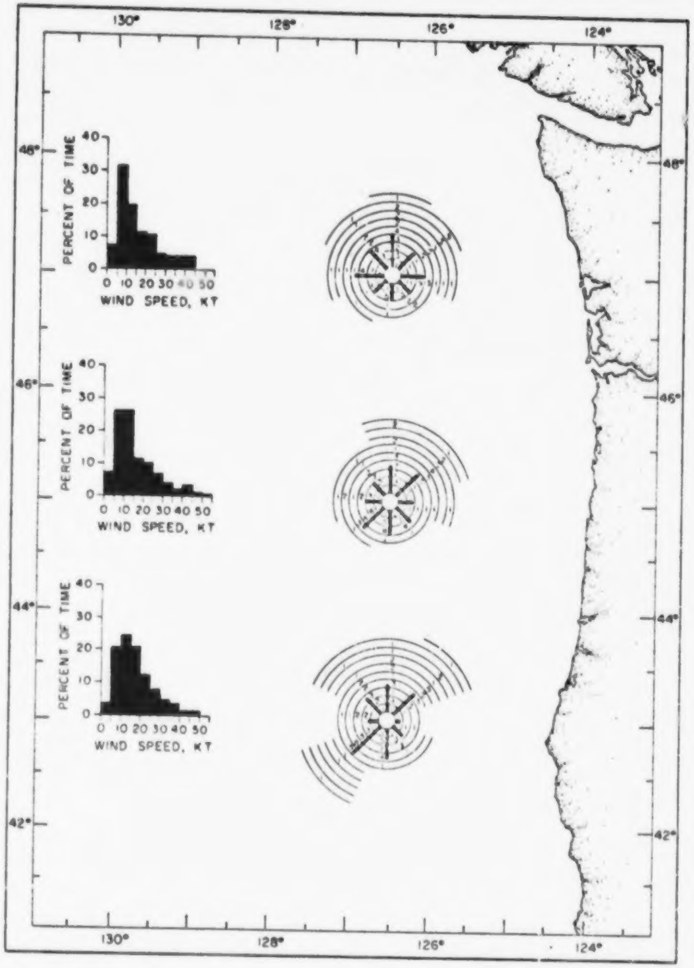


Fig. 5-4. Average direction and velocity of January winds for 1961-1963.

(from Duxbury, et al., 1128)

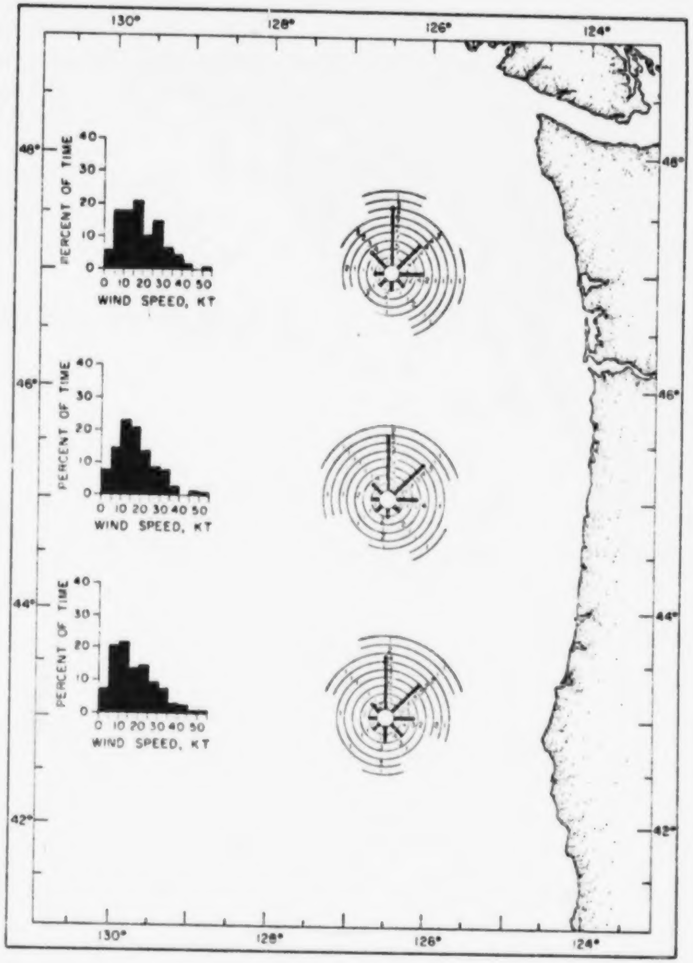


Fig. 5-5. Average direction and velocity of February winds for 1961-1963.

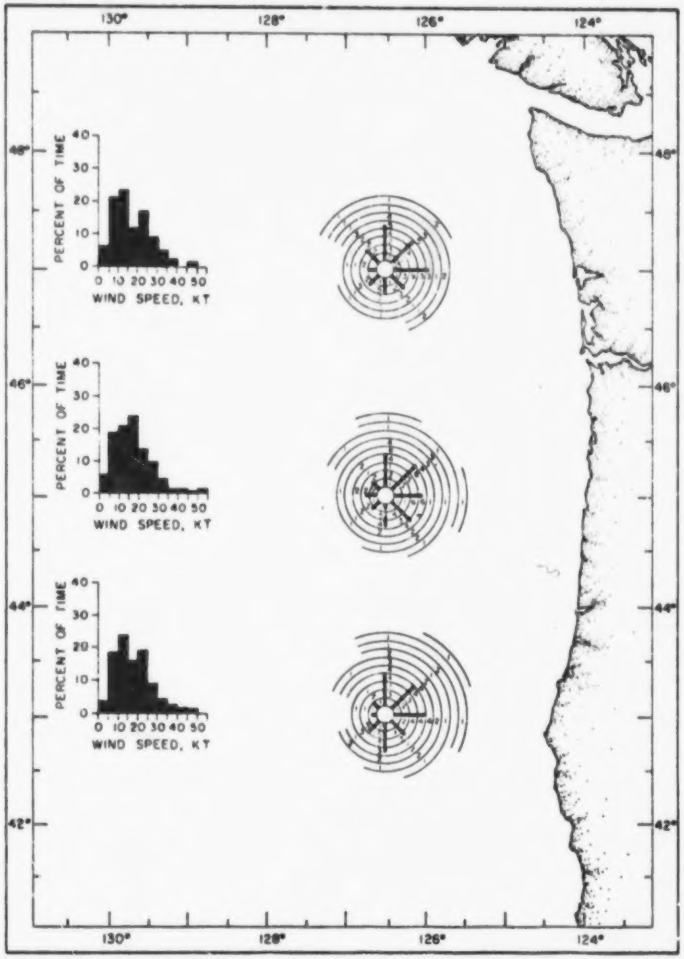


Fig. 5-6. Average direction and velocity of March winds for 1961-1963.

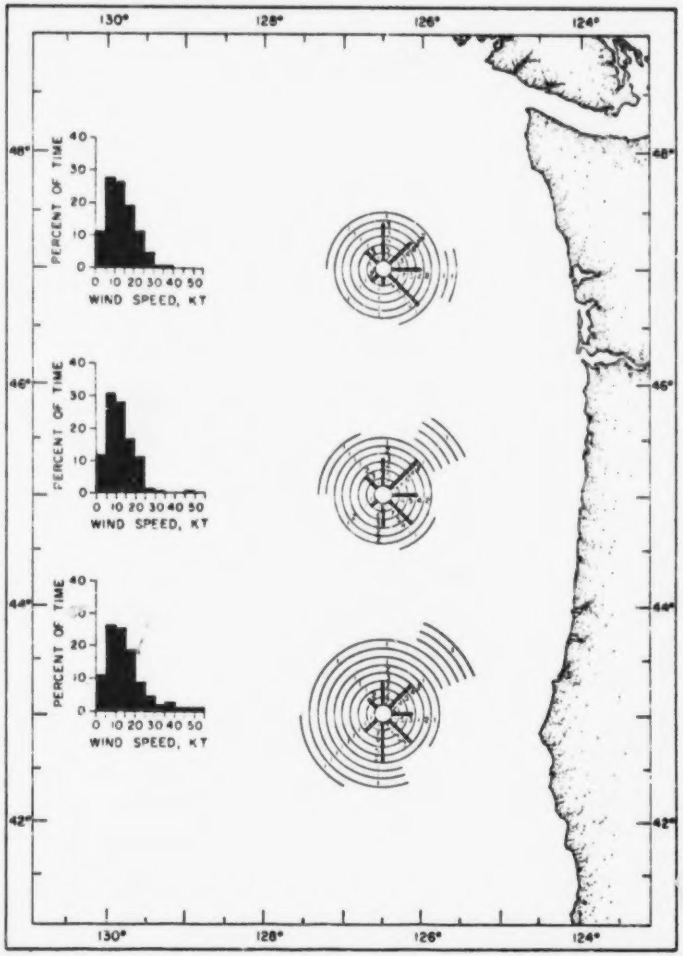


Fig. 5-7. Average direction and velocity of April winds for 1961-1963.

(from Duxbury, et al., 1128)

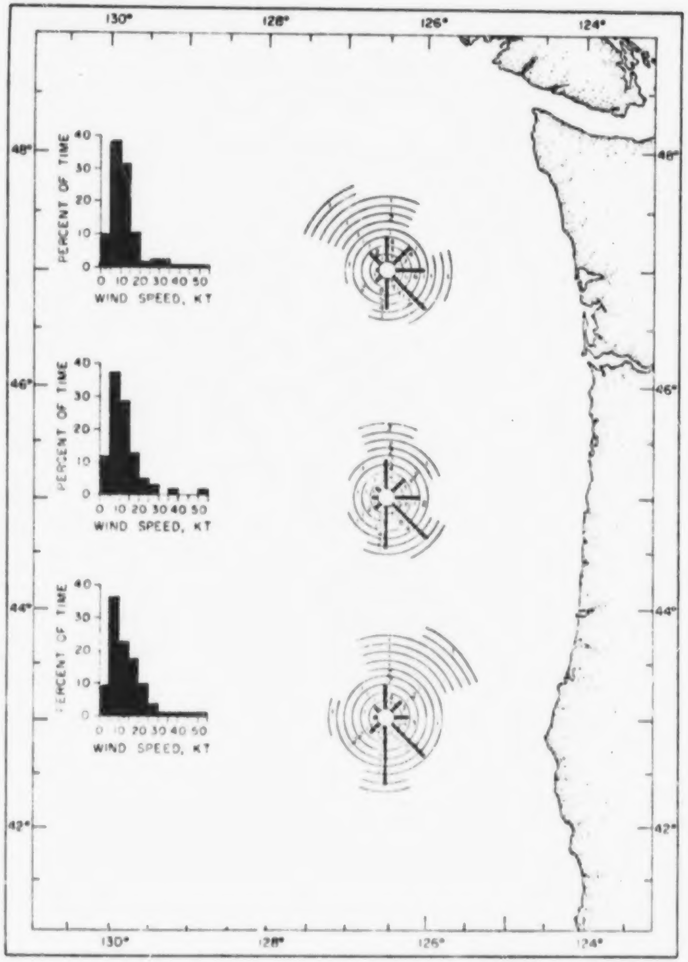


Fig. 5-8. Average direction and velocity of May winds for 1961-1963.

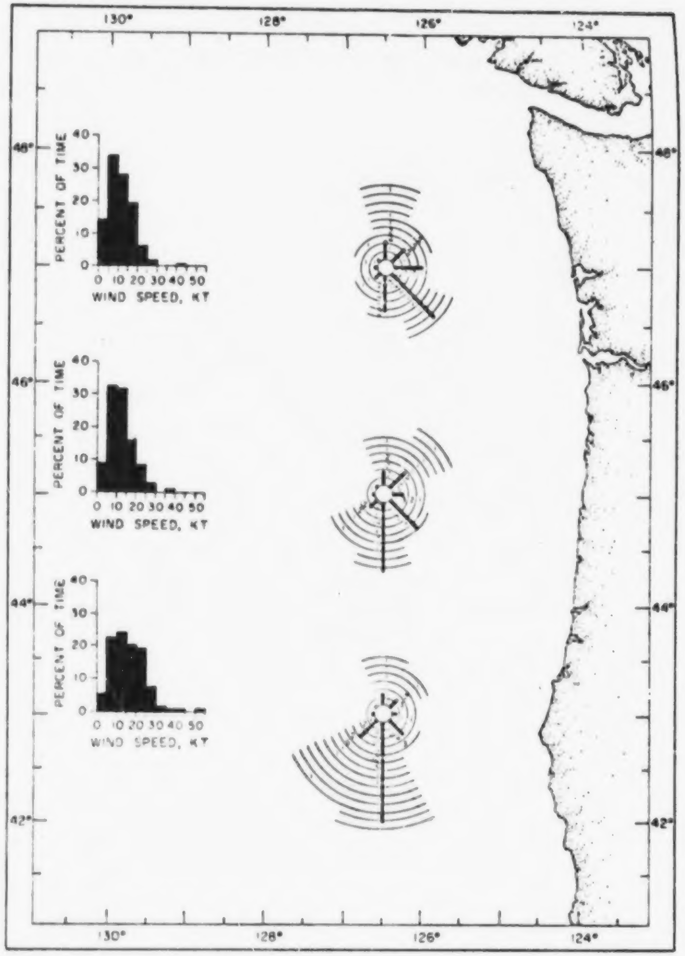


Fig. 5-9. Average direction and velocity of June winds for 1961-1963.

(from Duxbury, et al., 1128)

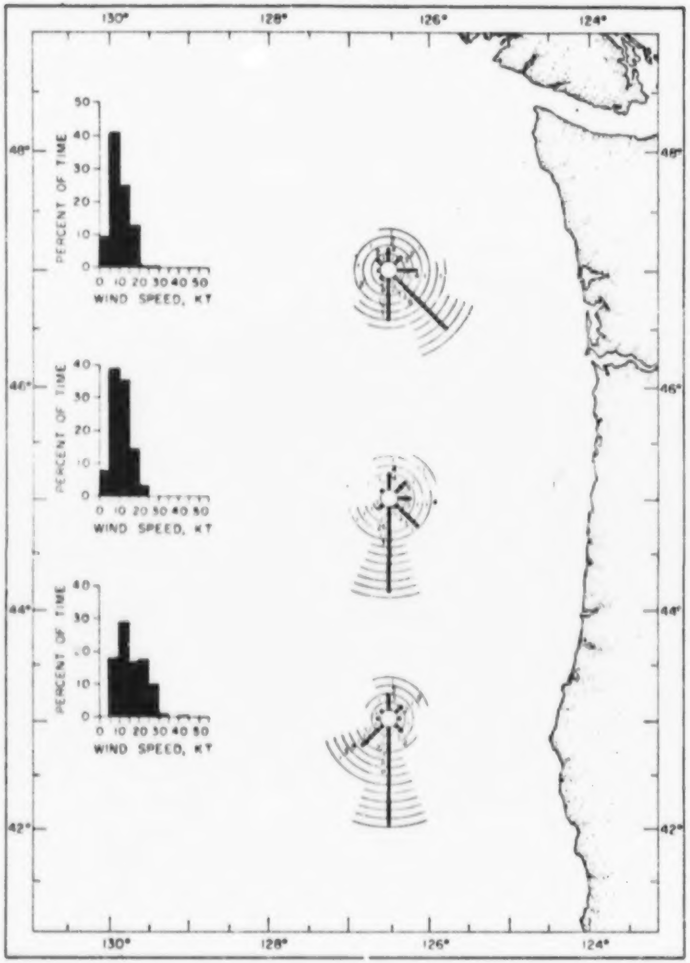


Fig. 5-10. Average direction and velocity of July winds for 1961-1963.

(from Duxbury, et al., 1128)

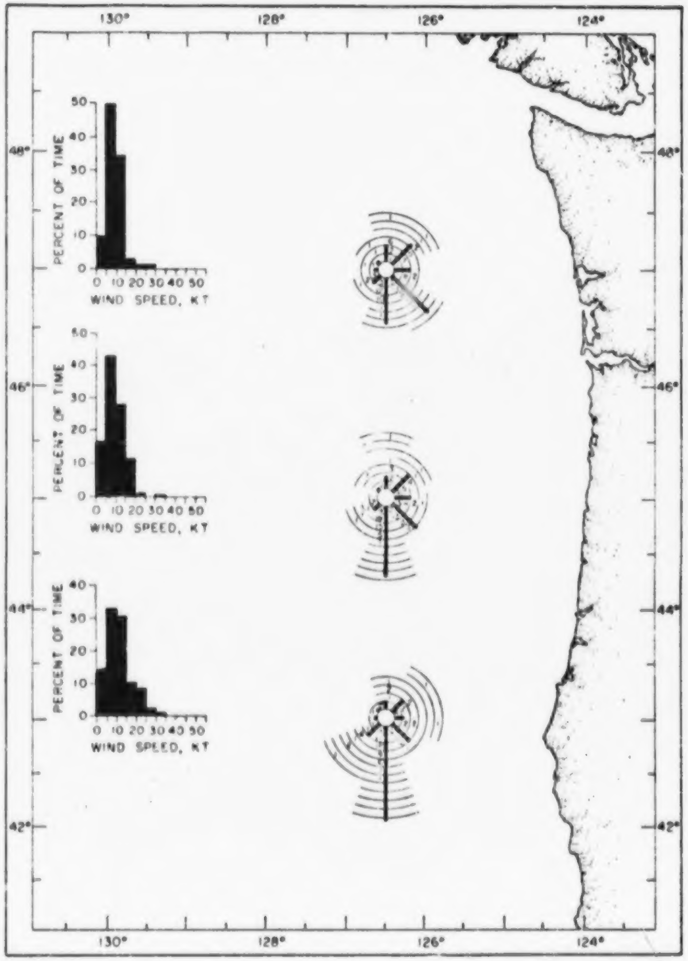


Fig. 5-11. Average direction and velocity of August winds for 1961-1963.

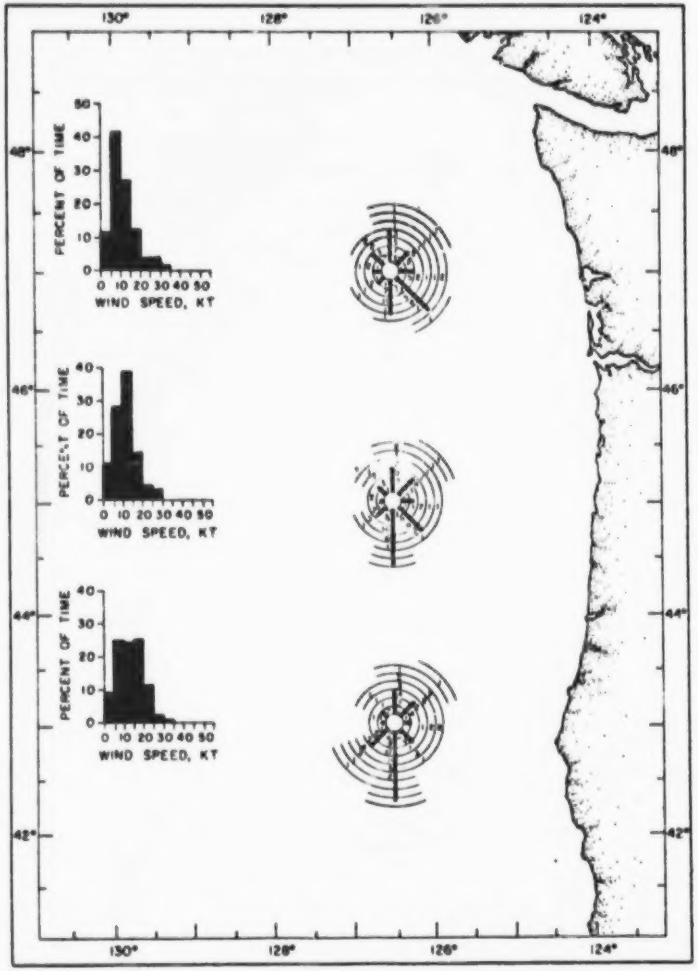


Fig. 5-12. Average direction and velocity of September winds for 1961-1963.

(from Duxbury, et al., 1128)

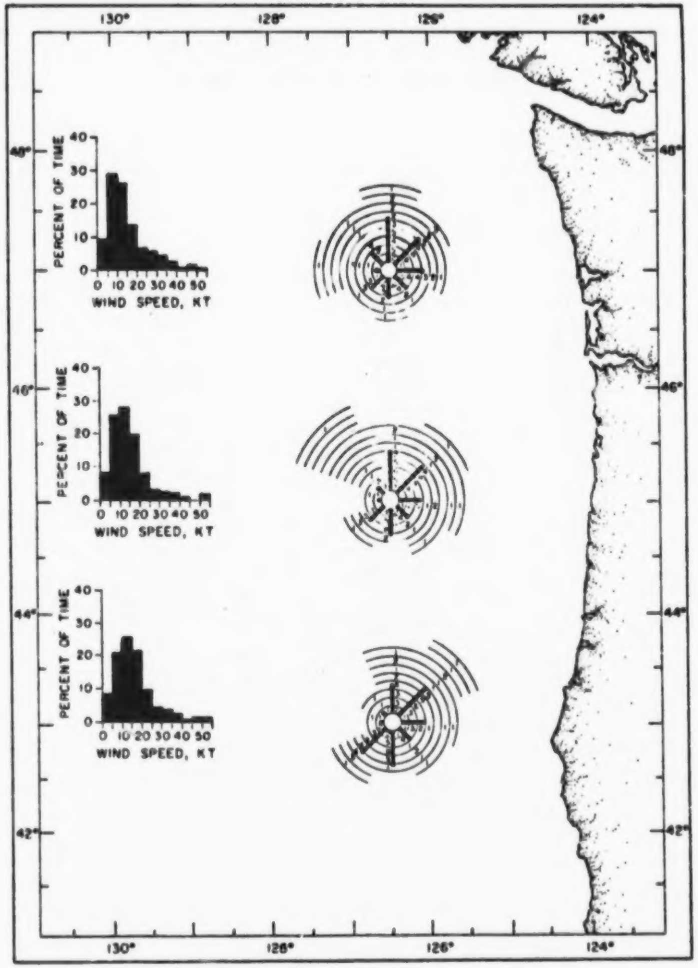


Fig. 5-13. Average direction and velocity of October winds for 1961-1963.

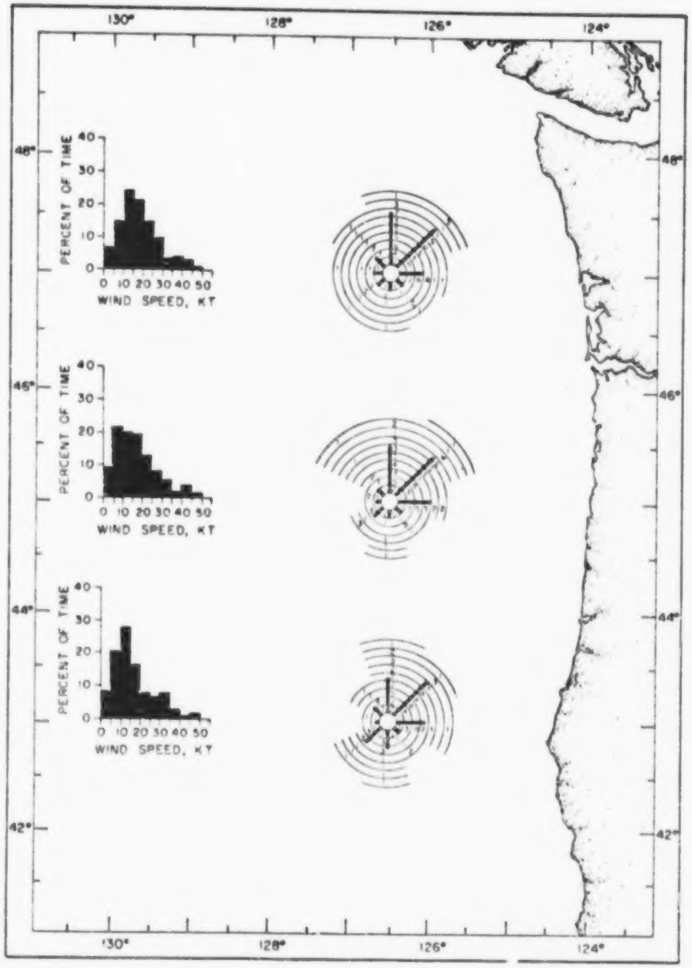


Fig. 5-14. Average direction and velocity of November winds for 1961-1963.

(from Duxbury, et al., 1128)

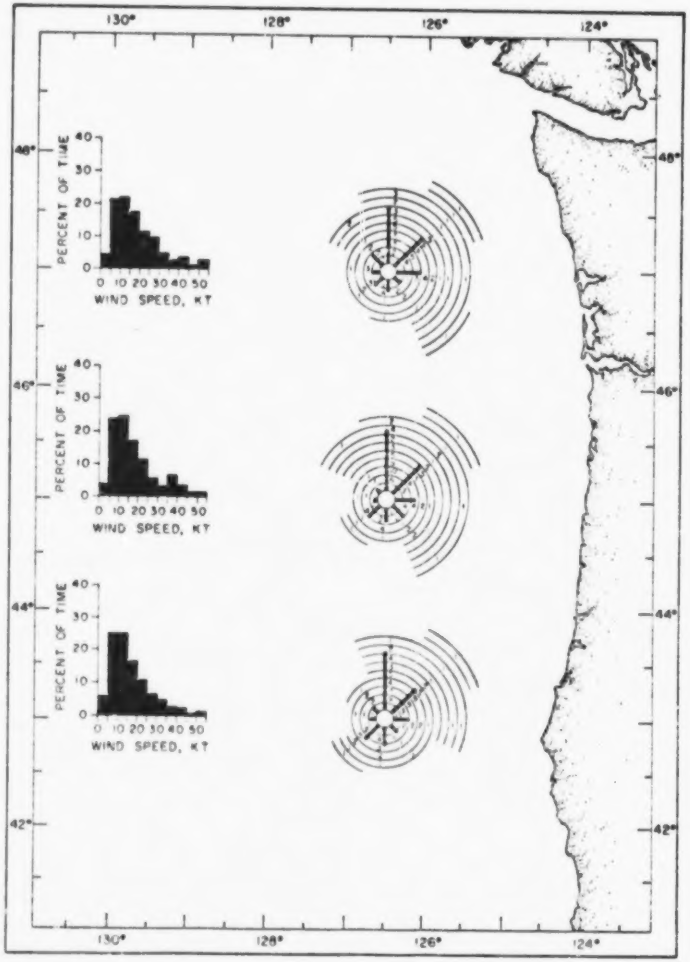


Fig. 5-15. Average direction and velocity of December winds for 1961-1963.

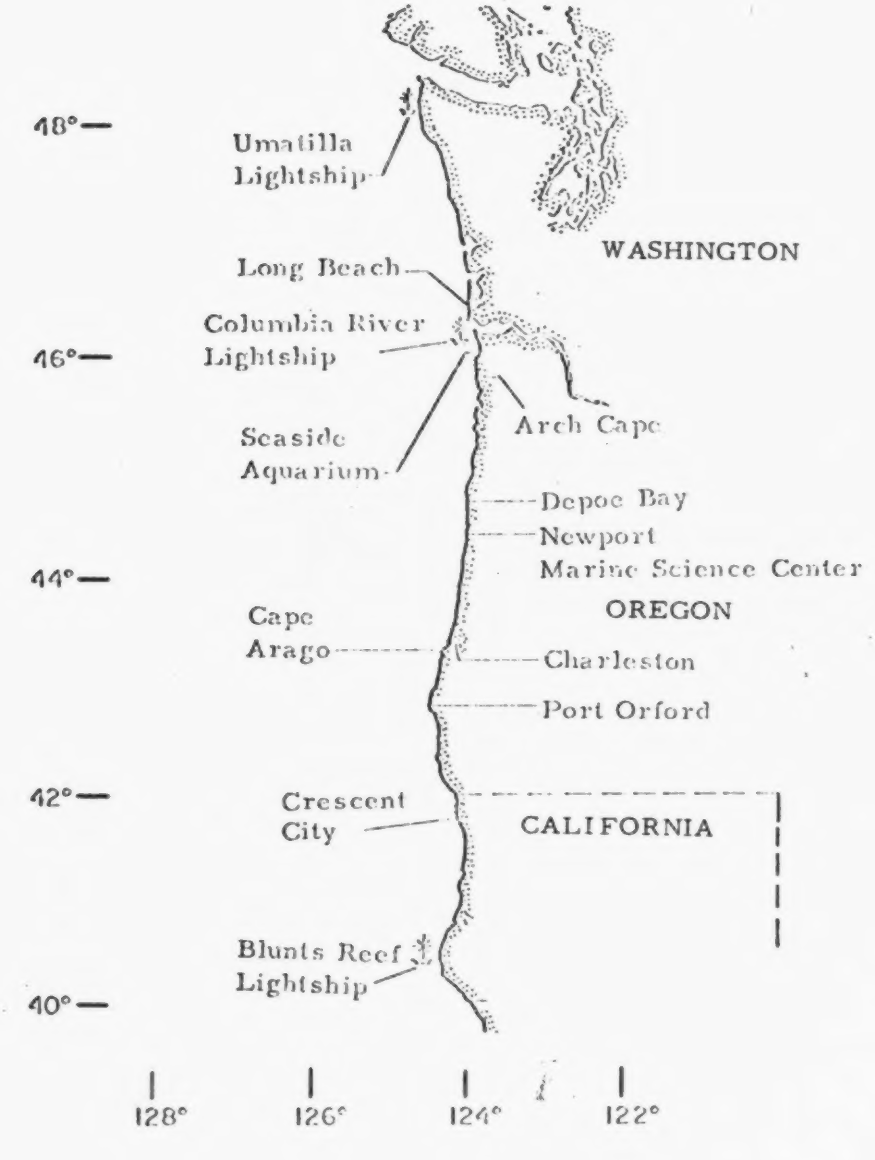


Figure 6-1. Location of shore stations and lightships along the Pacific Northwest coast.

Chapter 6. TEMPERATURE AND SALINITY

by Robert H. Bourke and Bard Glenne

Shore Station and Lightship Observations

Temperature and salinity observations are limited to mostly surface observations. Only data from the National Oceanographic Data Center contained subsurface observations and these were extremely limited. Hence, the emphasis of this chapter must be on the surface temperature and salinity of the area.

Observations of surface temperature and salinity have been made at selected shore stations and from three lightships along the Pacific Northwest Coast. Daily observations have been reported from the Blunts Reef Lightship off Cape Mendocino since 1923 and from Crescent City, California since 1934 (U. S. Dept. of Commerce, 1205). The Department of Oceanography at Oregon State University began reporting weekly observations from shore stations along the Oregon Coast in 1961 (OSU, Dept. of Ocean., 1169). Since 1964 all observations from reporting stations have been made daily (OSU, Dept. of Ocean., 1170). Data from the Umatilla Lightship are listed in a similar publication of the Scripps Institute of Oceanography, (1187). The location of each reporting station is shown in Figure 6-1 and Table 6-1.

Additional temperature and salinity samples have been collected from other sites along the Pacific Northwest Coast. Some of these data have been published (Burt, et al., 1115; Gonor, 1135; Neal, et al., 1160; Pearson and Holt, 1175; Skeesick, 1189) and some exist as unpublished laboratory reports (Frolander, 1133; Snow, 1190). The majority of these observations were taken during a single season or month in conjunction with research concerning the ecology of organisms living in the surf zone. These records were not considered sufficiently long to establish annual trends and were not included in the analyses to follow.

Tables 6-2 and 6-3 list by month the average mean, average maximum, and average minimum surface temperature and salinity and the total number of observations for each reporting station computed over the period of record. Salinities were determined from hydrometer readings; the few stations reporting salinities in excess of 34.5‰ are probably in error (1170).

Figures 6-2 through 6-5 are graphs of the monthly mean temperatures for the three lightship stations and for several shore stations along the Oregon-California coastline. At all locations there is a 4 to

Table 6-1. List of Shore Stations and Lightships in Geographical Order

Station Name	Position	Location
Washington		
Umatilla Lightship	48°10.0'N, 124°50.0'W	Off Cape Alava
Long Beach	46°23.0'N, 124°04.0'W	In surf on sand beach, 10th Street approach
Oregon		
Columbia River Lightship	46°11.2'N, 124°11.0'W	Mouth of Columbia River
Seaside Aquarium	45°59.7'N, 123°55.6'W	At pump outlet into Aquarium settling tank from surf inlet pipe
Arch Cape	45°48.0'N, 123°58.0'W	In surf on a sand beach
Depoe Bay Aquarium	44°49.4'N, 124°04.0'W	At pump outlet into Aquarium settling tank from surf inlet pipe
Newport Marine Science Center	44°37.2'N, 124°01.5'W	At pump outlet into Laboratory from bottom of Yaquina Bay
Charleston	43°21.0'N, 124°19.0'W	From surface of bay
Cape Arago Light Station	43°20.3'N, 124°22.5'W	Off the rocks below the Light Station
Port Orford	42°44.6'N, 124°30.6'W	Off east side of Port Orford River
California		
Crescent City	41°44.6'N, 124°11.7'W	USCGS Tide Guage Station, Crescent City
Blunts Reef Lightship	40°26.0'N, 124°30.0'W	Off Cape Mendocino

Table 6-2. Average monthly temperature (°C) and salinity (‰) of the surf measured at selected sites on the Pacific Northwest coast. Salinities enclosed by ( ) indicate average computed from fewer observations than listed in total.

Station and Period of Record		Monthly Avgs. & Total No. Obs.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Long Beach, Washington 1962-1963	T	Avg. Mean	-----	-----	-----	8.10	10.58	11.55	14.86	15.06	13.47	12.96	11.10	9.00
		Avg. Maximum				8.40	12.50	14.30	15.81	17.07	14.38	15.10	11.90	9.60
		Avg. Minimum				7.80	7.50	9.40	13.61	13.71	12.43	11.90	10.10	8.40
		Total No. Obs.				2	5	4	12	15	4	5	4	2
	S	Avg. Mean	-----	-----	-----	26.02	21.98	30.62	25.65	29.20	28.54	28.93	27.36	27.36
		Avg. Maximum				26.46	25.07	31.88	27.36	33.08	30.00	30.62	30.14	29.14
		Avg. Minimum				25.58	18.40	29.23	24.46	24.71	27.15	27.25	24.38	25.58
		Total No. Obs.				2	5	3	6	6	4	5	4	2
Seaside Aquarium 1966-1969	T	Avg. Mean	9.44	9.27	9.78	11.05	12.32	15.04	15.08	14.63	15.26	13.73	12.49	10.82
		Avg. Maximum	10.65	9.95	10.55	12.03	14.33	16.97	17.68	16.61	16.12	15.30	13.77	12.07
		Avg. Minimum	8.42	8.73	8.89	9.97	10.59	12.97	12.14	12.17	14.22	12.25	11.16	9.58
		Total No. Obs.	72	54	79	66	64	78	79	72	45	46	50	44
	S	Avg. Mean	28.14	28.23	28.39	28.52	29.11	26.83	28.98	31.19	30.41	29.79	30.15	28.95
		Avg. Maximum	29.81	30.34	30.36	30.41	31.69	30.92	32.70	32.48	31.64	30.85	30.52	29.79
		Avg. Minimum	26.09	25.65	24.48	24.67	24.83	21.65	23.22	29.48	27.56	27.95	28.25	27.75
		Total No. Obs.	69	55	77	66	64	78	79	72	45	46	50	44
Arch Cape 1960-1963 (1961 dominates salinity data)	T	Avg. Mean	9.35	9.85	9.33	10.55	12.29	12.80	14.18	12.76	12.15	11.84	10.57	9.43
		Avg. Maximum	10.20	10.27	10.70	11.99	13.61	15.20	17.56	15.88	14.78	12.74	12.03	10.10
		Avg. Minimum	8.11	9.07	8.21	9.37	10.62	10.19	9.85	9.77	9.65	9.15	8.82	8.73
		Total No. Obs.	44	37	51	41	41	42	67	72	83	41	37	66
	S	Avg. Mean	30.68	30.51	30.22	29.12	28.70	31.30	31.52	32.76	32.46	32.31	31.53	30.13
		Avg. Maximum	31.45	31.64	31.70	32.43	31.46	33.62	33.45	33.89	33.41	33.35	32.96	31.57
		Avg. Minimum	28.87	30.00	27.55	26.65	26.52	27.75	28.77	30.99	31.44	30.93	29.75	26.98
		Total No. Obs.	8	7	25	38	44	32	40	40	42	36	29	41

Table 6. 2. continued

			Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Depoe Bay Aquarium 1965-1969 (July and August salinity averages based on one year only)	T	Avg. Mean	9.23	9.28	9.33	10.35	10.66	13.10	12.06	15.81	14.48	12.83	11.28	9.96
		Avg. Maximum	9.94	9.84	10.05	11.31	11.84	15.14	13.43	16.84	15.90	13.70	12.26	10.89
		Avg. Minimum	8.48	8.65	8.28	9.50	9.67	11.47	11.00	14.25	13.05	11.61	10.06	8.87
		Total No. Obs.	82	69	74	80	60	49	23	44	55	48	58	85
	S	Avg. Mean	30.90	31.33	31.04	31.40	32.31	32.08	31.97	30.33	32.32	32.82	32.38	31.51
		Avg. Maximum	31.93	32.11	32.31	32.57	33.10	33.82	33.00	30.99	33.00	33.83	33.19	33.00
		Avg. Minimum	29.53	30.42	29.67	31.05	31.33	30.41	30.10	28.28	31.00	31.91	31.70	30.16
		Total No. Obs.	82	69	74	59	40	48	3	23	32	40	58	85
Newport Marine Science Center 1965-1969	T	Avg. Mean	9.33	9.44	9.75	10.27	12.38	13.39	12.60	12.30	13.38	11.53	11.96	10.94
		Avg. Maximum	10.27	10.74	10.32	11.21	13.61	13.82	15.46	14.92	15.30	13.54	13.75	11.97
		Avg. Minimum	8.55	8.63	8.96	9.42	9.68	12.30	9.57	9.90	10.63	10.76	10.85	9.63
		Total No. Obs.	74	64	65	64	78	78	54	66	43	43	68	70
	S	Avg. Mean	29.40	30.06	30.00	31.28	31.98	31.87	32.59	33.31	32.83	32.59	31.27	29.54
		Avg. Maximum	31.69	31.78	31.93	32.89	33.59	33.16	33.73	33.74	33.41	33.15	32.48	31.41
		Avg. Minimum	25.83	24.94	26.75	29.39	29.49	28.61	29.86	32.51	31.97	31.73	29.75	26.07
		Total No. Obs.	85	75	64	77	81	79	58	77	63	65	70	70
Charleston 1966-1969	T	Avg. Mean	9.37	9.89	10.64	11.17	11.60	13.05	12.92	12.43	13.66	12.41	11.20	10.26
		Avg. Maximum	10.80	11.28	12.04	12.38	13.81	15.71	15.33	13.96	15.70	14.62	12.68	11.50
		Avg. Minimum	7.70	8.81	9.51	9.71	9.98	11.57	10.54	10.45	11.35	10.74	9.47	9.06
		Total No. Obs.	64	35	42	46	55	65	76	44	45	64	41	63
	S	Avg. Mean	30.07	29.28	30.20	30.65	31.60	32.19	32.57	32.83	32.58	31.58	30.56	29.91
		Avg. Maximum	31.88	31.56	31.44	31.79	(33.16)	(33.48)	(33.42)	33.42	33.51	32.90	32.75	32.07
		Avg. Minimum	25.32	27.26	27.58	27.55	28.78	30.26	31.21	31.93	30.93	30.27	27.54	27.05
		Total No. Obs.	64	34	42	46	54	65	71	33	47	57	41	63
Cape Arago Light Station 1963-1966	T	Avg. Mean	9.52	9.55	9.81	10.45	11.37	12.47	12.74	13.29	13.00	12.75	12.34	10.96
		Avg. Maximum	10.54	10.20	11.93	11.98	12.95	14.47	15.04	16.08	15.13	14.02	13.44	12.72
		Avg. Minimum	7.61	8.90	8.24	9.55	9.95	11.05	10.30	10.81	10.49	11.32	11.20	9.00
		Total No. Obs.	41	25	68	84	91	85	88	88	64	84	67	52
	S	Avg. Mean	30.86	32.48	32.17	32.05	31.72	32.90	33.32	33.53	33.35	32.84	32.53	31.78
		Avg. Maximum	32.61	33.58	(33.20)	(32.87)	(32.82)	(33.70)	>34.00	>34.00	>34.00	(33.55)	(32.96)	32.98
		Avg. Minimum	27.74	31.36	30.69	29.96	28.72	31.73	32.10	32.36	32.43	32.14	31.35	29.59
		Total No. Obs.	39	25	67	84	73	85	88	86	64	84	67	52

Table 6-2. continued

			Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Port Orford 1964-1969	T	Avg. Mean	9.76	10.24	9.85	9.88	9.89	10.89	10.90	11.58	12.35	11.83	11.12	10.71
		Avg. Maximum	10.73	11.05	10.89	11.00	11.29	12.76	13.96	14.10	14.41	12.87	11.52	11.58
		Avg. Minimum	8.32	9.75	8.93	8.62	8.48	9.33	9.14	9.40	10.43	10.89	10.45	9.71
		Total No. Obs.	99	101	126	107	113	90	110	97	90	70	25	76
	S	Avg. Mean	31.68	31.73	32.08	32.36	33.34	33.61	33.71	33.71	33.30	32.94	32.59	31.20
		Avg. Maximum	32.68	32.75	(33.10)	(32.62)	(33.76)	>34.00	>34.00	>34.00	(33.49)	(33.42)	33.27	32.20
		Avg. Minimum	29.97	30.26	30.17	31.20	32.20	32.60	33.02	32.99	32.83	32.20	31.83	30.02
		Total No. Obs.	99	98	126	107	113	89	110	96	90	80	25	75
Crescent City, California 1934-1964	T	Avg. Mean	9.7	10.0	10.2	10.8	11.7	12.5	13.5	14.2	13.5	12.1	11.1	10.3
		Avg. Maximum	11.0	11.2	11.6	12.2	13.4	14.7	15.3	15.8	15.2	13.6	12.5	11.6
		Avg. Minimum	8.1	8.4	8.7	9.5	10.0	10.6	11.4	12.3	11.7	10.8	9.5	8.7
1963-1969	S	Avg. Mean	28.30	28.98	29.69	28.84	30.40	31.77	32.54	32.33	32.75	32.60	30.90	29.64
		Avg. Maximum	31.99	(32.07)	(32.63)	32.35	33.75	(33.71)	(32.77)	33.08	33.62	33.33	32.74	32.31
		Avg. Minimum	22.90	23.05	23.55	22.14	25.00	29.08	30.42	31.28	31.56	31.71	28.01	25.49
		Total No. Obs.	106	102	90	81	51	71	60	61	99	96	96	55

Table 6-3. Average monthly surface temperature (°C) and salinity (‰) from three lightships off the Pacific Northwest coast. Salinities enclosed by ( ) indicate average computed from fewer observations than listed in total.

Station and Period of Record		Monthly Avgs. & Total No. Obs.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Umatilla Reef Lightship 1966-1969	T	Avg. Mean	9.11	8.16	8.49	9.26	10.29	12.40	12.67	12.56	14.05	12.00	10.97	9.40
		Avg. Maximum	10.40	9.10	9.11	11.68	13.07	15.50	14.60	14.58	16.39	14.11	12.04	11.03
		Avg. Minimum	7.97	7.49	7.68	7.62	8.85	12.82	11.22	10.18	11.79	10.64	9.53	8.42
		Total No. Obs.	93	57	65	73	88	119	94	88	83	80	80	78
	S	No data.												
Columbia River Lightship 1965-1969	T	Avg. Mean	9.30	8.82	9.20	10.10	11.50	13.64	14.56	14.91	14.92	13.83	12.14	10.00
		Avg. Maximum	10.61	10.63	10.06	11.37	13.07	15.56	16.50	17.07	16.48	15.17	13.46	11.89
		Avg. Minimum	7.55	7.53	8.03	9.22	12.39	11.41	12.71	12.65	12.89	12.29	10.56	7.90
		Total No. Obs.	77	118	112	109	123	151	152	117	93	89	112	103
	S	Avg. Mean	27.99	26.90	26.69	24.17	25.18	22.76	23.07	27.27	31.15	30.35	27.80	22.72
		Avg. Maximum	(33.20)	32.11	32.04	29.72	29.43	29.88	26.90	30.60	(33.50)	(33.43)	30.48	30.94
		Avg. Minimum	19.29	21.23	17.02	16.18	19.95	14.80	12.55	21.48	23.00	21.36	24.12	13.18
		Total No. Obs.	55	55	95	78	96	107	117	81	58	63	94	53
Blunts Reef Lightship 1923-1964	T	Avg. Mean	11.0	10.8	10.4	10.2	10.3	10.3	10.2	10.8	11.3	11.6	11.7	11.5
		Avg. Maximum	12.1	11.8	11.6	11.4	12.0	12.2	11.9	12.7	13.3	13.6	13.3	12.9
		Avg. Minimum	10.1	9.9	9.1	8.9	9.1	8.9	8.9	9.4	9.9	10.1	10.1	10.1
1966-1968	S	Avg. Mean	33.16	33.08	32.86	33.26	33.73	33.75	33.84	33.59	33.42	33.52	33.20	33.06
		Avg. Maximum	33.68	33.62	33.52	(33.[illegible]4)	> 34.00	> 34.00	> 34.00	> 34.00	33.89	33.87	33.73	33.49
		Avg. Minimum	32.23	32.12	31.39	32.10	33.07	33.36	33.24	32.91	33.02	32.98	32.70	32.55
		Total No. Obs.	62	57	89	84	90	89	92	86	88	93	89	55

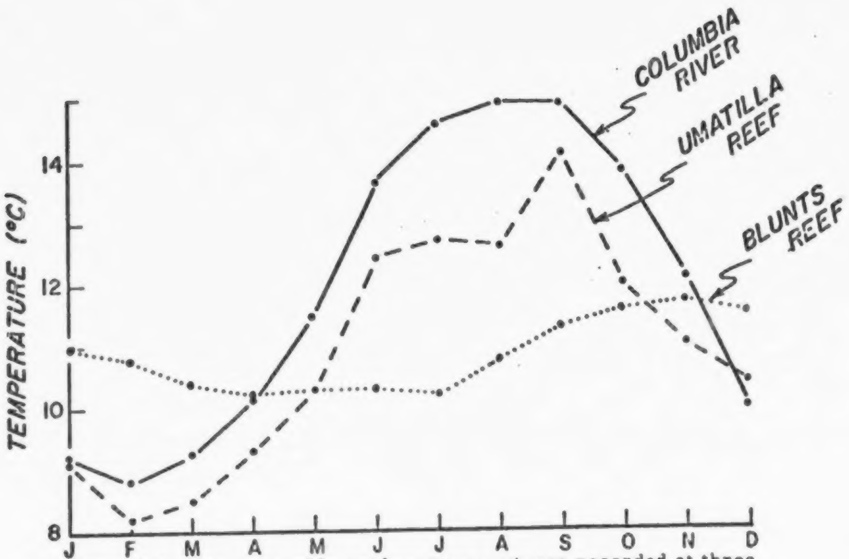


Figure 6-2. Mean monthly surface temperatures recorded at three lightships along the Pacific Northwest Coast. Monthly means were computed from daily observations taken over the periods listed in Table 6-3. Note that the annual range for the southernmost lightship is much less than that of the more northerly stations.

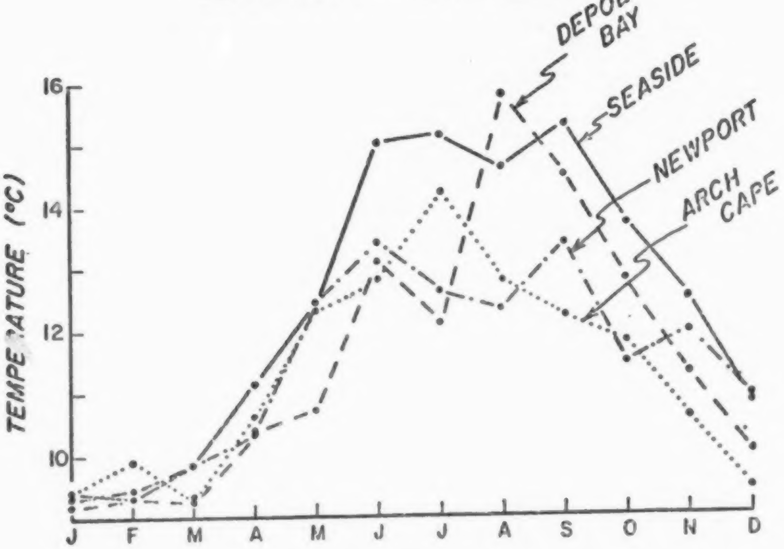


Figure 6-3. Mean monthly surface temperatures recorded at four northern Oregon shore stations. Monthly means were computed from daily observations taken over the periods listed in Table 6-2. The high summer temperatures reflect the influx of the warm Columbia River discharge.

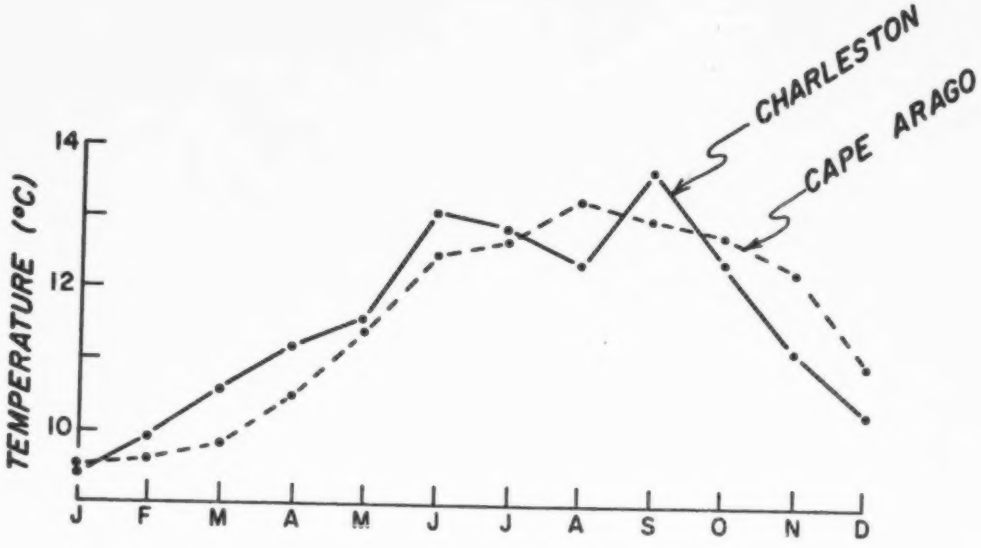


Figure 6-4. Mean monthly surface temperatures measured at shore stations in Coos Bay area. Monthly means were computed from daily observations over a four year period (Table 6-2).

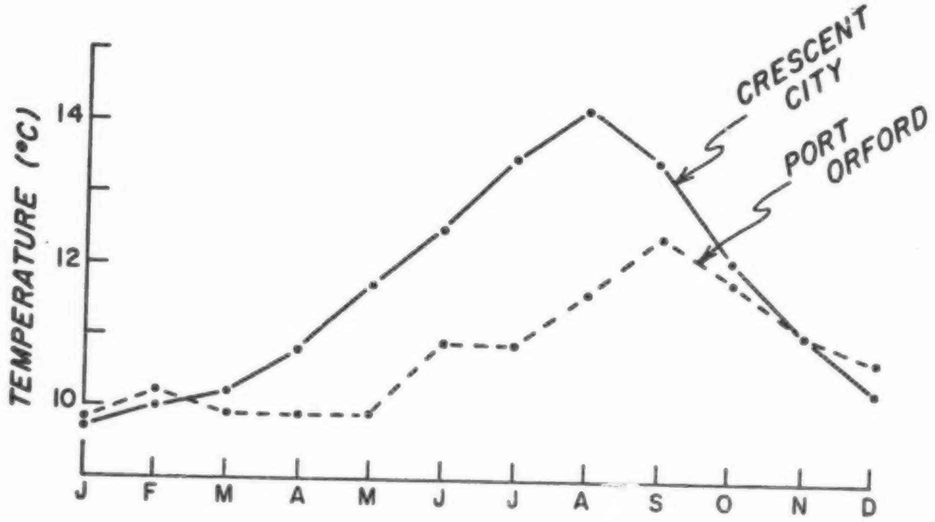


Figure 6-5. Mean monthly surface temperatures measured at shore stations south of Cape Blanco. Monthly means were computed from daily observations taken over the periods listed in Table 6-2. Note that the intense upwelling characteristic of the Cape Blanco area is reflected in the low summer temperatures at Port Orford.

5 C° increase in temperature during the summer months. The northern stations experience a larger range in annual temperatures than do the southern stations (Tables 6-2 and 6-3). Maximum temperatures are usually achieved during August or September. The surface waters are coldest from December through March.

The range between average maximum and minimum monthly temperatures is larger during summer than winter. Summer temperatures can be expected to fluctuate approximately 2.5 to 3.0 C° about the monthly mean temperature; during winter this fluctuation is approximately 0.5 to 1.0 C°.

The surface temperatures observed during summer from the Columbia River Lightship, 5 miles offshore, are influenced by the river discharge temperature as indicated by the anomalously high average mean and average maximum temperatures of 14.9°C and 17.1°C, respectively. The three northerly stations on the Oregon Coast also had average maximum temperatures in excess of 17°C; at the southerly stations maximum temperatures were usually 14 to 15°C. The high summer temperature of the Columbia River discharge undoubtedly caused the higher temperatures observed at these northern stations. This corroborates the findings of Pattullo and Denner (1173) based on a shorter observation period.

The temperature patterns observed from the Blunts Reef Lightship off Cape Mendocino and at Port Orford just south of Cape Blanco are unlike those observed at other stations. These stations are located in regions of extremely active upwelling. During periods of upwelling (June-September) the near surface waters of these regions can be expected to be relatively cool and quite saline. Average minimum temperatures are low, 8 to 9°C, and surface salinities often exceed 34‰. The increase in summer temperatures observed at the other stations does not occur. Maximum temperatures occur in October and November, two months after the other stations have reached their maximums. The range in temperature at these two stations is small, approximately 1 C° in winter and 2 C° in summer.

Offshore Temperature and Salinity Observations

Temperature and salinity observations from vessels at sea are on file at the National Oceanographic Data Center (NODC). These data are filed by 10° Marsden square numbers (Schuyler, 1225); number 157 encompasses the region of the study area. Data from one degree squares 40° to 48°N latitude and 124° to 125°W longitude within Marsden square 157 were obtained from NODC. Since this report is concerned with the data observed within 10 miles (18 km) of the coast (the distance between 124°W and 125°W longitude is about 48 miles), a computer program was written to exclude all data observed more than 10 miles from shore. About 25 percent of the original data was found shoreward of this 10-mile boundary. After arranging the data by month and latitude, it was apparent that an extreme paucity of data existed and that most observations were clustered about the major coastal towns or off prominent headlands. More than 50 percent of the observations were from the vicinity of the Columbia River mouth.

Monthly means of temperature and salinity, maximum and minimum values, and number of observations have been computed for the standard depths of 0, 10, 20, 30, and 50 meters for the clustered data areas. Table 6-4 is a listing of average surface conditions. Similar statistics for the remaining depths are listed in Appendix 2 of Volume II.

Care should be exercised when using the data in Table 6-4 since:

1. Very few observations were available to compute a meaningful average. Frequently only 1 to 3 observations were used to compute the monthly averages.

2. The observations for a given month are not necessarily from the same year, but may have been taken over a span of 10 years.

3. The data represent average surface conditions over an area about 5 miles wide. Airborne infrared surveys have shown temperatures to increase with distance from the coast in this 5-mile wide zone.

With the above in mind, the following observations seem significant regarding the offshore temperature and salinity distribution:

1. a. For the Coos Bay, Brookings, and Trinidad Head offshore areas, coldest temperatures (7-9 °C) occur in June. Salinities are also high in June (>33.6‰) indicating strong upwelling.

b. Maximum temperatures at the above three offshore stations are reached in September and October (12-13°C). Salinities remain high throughout the summer (>33.0‰).

Table 6-4. Mean monthly surface temperatures (°C) and salinities (‰) for selected offshore areas (1-10 km from the coast). Data are from that on file at NODC. Note the very few number of observations available for computation of monthly averages.

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Humboldt Bay Area	**Mean Temp.**	11.04	11.19	10.31	9.14	11.72	12.21	12.80	13.24	12.76	11.49	-----	11.34
40°49' to 40°51'	**No. of Obs.**	10	3	5	6	3	13	3	7	7	6		7
	Mean Salinity	32.76	30.16	30.60	33.73	31.68	33.55	33.38	33.33	33.65	33.32	-----	30.67
	No. of Obs.	10	3	5	6	3	12	3	7	7	6		8
Trinidad Head Area	**Mean Temp.**	-----	-----	-----	10.93	-----	9.47	13.66	12.63	13.32	12.42	-----	-----
41°03' to 41°04'	**No. of Obs.**				1		3	10	2	8	1		
	Mean Salinity	-----	-----	-----	32.12	-----	33.93	33.35	-----	33.56	33.35	-----	-----
	No. of Obs.				1		3			8	1		
Brookings Area	**Mean Temp.**	-----	-----	10.86	-----	11.66	6.50	11.08	11.48	12.66	11.05	-----	9.71
42°00'	**No. of Obs.**			1		5	1	1	1	1	1		1
	Mean Salinity	-----	-----	-----	-----	31.57	34.06	33.62	33.85	33.53	33.00	-----	32.72
	No. of Obs.					5	1	1	1	1	1		1
Coos Bay Area	**Mean Temp.**	9.20	-----	10.10	11.19	11.71	8.46	10.60	11.05	13.24	13.46	10.79	10.44
43°20' to 43°21'	**No. of Obs.**	1		7	1	1	1	3	2	2	3	2	3
	Mean Salinity	32.36	-----	31.95	30.93	32.17	33.58	33.23	33.46	33.02	32.83	32.68	31.67
	No. of Obs.	1		7	1	1	1	3	2	2	3	2	3
Yaquina Head Area	**Mean Temp.**	9.68	9.45	10.55	10.52	10.75	11.47	9.65	11.80	12.97	12.15	11.94	10.41
44°38' to 44°41'	**No. of Obs.**	6	7	4	7	6	7	11	6	5	10	9	7
	Mean Salinity	32.17	31.03	31.13	31.03	32.05	32.13	33.06	33.14	32.71	32.55	32.14	31.66
	No. of Obs.	6		4	7	6	7	11	6	5	10	10	7
Tillamook Bay Area	**Mean Temp.**	10.26	8.16	10.29	9.42	13.25	12.01	8.44	12.76	14.18	15.33	-----	11.71
45°30' to 45°46'	**No. of Obs.**	1	1	1	1	4	6	1	2	4	3		2
	Mean Salinity	32.00	27.41	31.08	25.84	30.18	30.06	33.16	31.76	31.87	31.82	-----	31.53
	No. of Obs.	1	1	1	1	3	6	1	2	4	3		2
Seaside Area	**Mean Temp.**	-----	8.02	9.33	9.24	12.05	12.72	15.08	14.56	14.86	15.88	10.41	-----
45°58' to 46°05'	**No. of Obs.**		3	5	2	1	11	1	3	7	4	1	
	Mean Salinity	-----	24.76	27.74	27.36	30.31	24.71	29.05	28.80	27.35	31.38	32.16	-----
	No. of Obs.		3	5	2	1	11	1	3	7	4	1	
Columbia River Mouth Area	**Mean Temp.**	8.93	7.61	8.95	9.67	12.02	13.62	14.68	14.41	13.84	14.24	10.26	9.84
46°07' to 46°22'	**No. of Obs.**	5	37	28	11	10	110	2	51	155	10	9	5
	Mean Salinity	27.74	20.16	24.30	22.09	21.65	16.57	25.40	25.21	27.80	28.08	29.21	25.86
	No. of Obs.	4	37	27	11	9	117	2	51	156	10	9	6
Long Beach to Ocean Park Area	**Mean Temp.**	8.17	8.00	8.85	9.18	12.97	13.49	-----	13.58	13.90	14.91	10.60	8.84
46°22' to 46°36'	**No. of Obs.**	3	6	8	6	3	15		4	9	5	5	2
	Mean Salinity	27.92	26.29	27.37	27.40	30.24	21.87	-----	30.71	29.80	29.37	30.64	26.10
	No. of Obs.	3	6	8	6	3	15		4	9	5	5	2
Pacific Beach Area	**Mean Temp.**	9.28	8.24	9.26	9.49	-----	13.99	10.30	-----	15.00	14.70	-----	6.92
47°00' to 47°19'	**No. of Obs.**	1	2	3	1		4	1		3	1		1
	Mean Salinity	28.26	27.67	27.23	25.65	-----	27.19	33.43	-----	30.97	30.09	-----	26.98
	No. of Obs.	1	2	3	1		4	1		3	1		1

c. For the Yaquina Head and Tillamook Bay offshore areas, low temperatures (8-9°C) and high salinities (>33.0‰) are observed in July. Upwelling is dominant during July. Maximum temperatures (13-15 °C) occur in September and October after the cessation of upwelling.

d. Maximum temperatures at shore stations in these 5 areas occur two months earlier--in August and September.

2. a. At Seaside and for the Long Beach-Ocean Park areas, surface temperatures remain relatively high throughout the summer (14-15°C). Salinities rarely exceed 30.00‰. In June, the Columbia River flood is reflected in extremely low surface salinities (21-24‰).

b. Upwelling then, as measured by low temperatures and high salinities, does not appear to be a dominant factor in these two areas.

3. a. Examination of subsurface temperatures (Appendix 2) indicates that isothermal conditions (constant temperature with increasing depth) exist from November through March-April. This may permit surface temperatures to be inferred from subsurface temperature recorders during the winter months when it may be difficult to obtain continuous surface temperatures. A weak thermocline less than 2°C) exists during the summer at a depth of less than 20 meters. Continuous temperature measurements are available from thermograph records made 3 to 10 miles off the central Oregon coast near Depoe Bay and Yaquina Head. Observational periods include May and June, 1967; April through September, 1968; and July through September, 1969. Analysis of the 1967-1968 data is completed and will be published (Pillsbury et al., 1177).

Sea Surface Temperature from Infrared Surveys

The airborne infrared radiometer (radiation thermometer) has proven useful for mapping mesoscale distributions of sea surface temperature. Large scale features such as upwelling fronts or the plume from the Columbia River are readily apparent.

Since August 1963 the Tiburon Marine Laboratory of the Bureau of Sport Fisheries and Wildlife, Department of the Interior, in cooperation with the U. S. Coast Guard has conducted monthly infrared radiometer surveys for three Pacific coast areas. The recently modified northern flight pattern (the only area within the limits of this study) extends from Cape Elizabeth, Washington, to Newport, Oregon, and offshore to the 6000 foot (1000 fathoms) contour (approximately 60 miles offshore). Figure 6-6 is an example of the monthly temperature pattern constructed from one such survey.

During the summer of 1969 the Department of Oceanography, Oregon State University in conjunction with OSU's Sea Grant project, "Albacore Central," conducted daily infrared radiometer surveys, along the Oregon Coast to approximately 30 miles offshore. Temperature contours from a typical flight are shown in Figure 6-7.

Temperature profiles constructed from airborne infrared surveys within 5 miles of the coast are quite subjective. Figure 6-8 shows profiles from a segment of a typical survey conducted by OSU. The horizontal temperature gradient changes rapidly and unpredictably within the first 5 to 10 miles off the coast. Discontinuities marking temperature fronts are present and can be corroborated by abrupt changes in water color. In order to construct representative sea surface temperature contours with some degree of confidence, closer spacing of the flight track is required than that shown in Figure 6-8.

Conclusions

1. An abundant source of surface temperature and salinity data is available from coastal shore stations and the three offshore lightships. Few measurements have been made, however, inside of this five mile wide zone.

2. Surface temperatures range from an average high of 17.7°C to an average low of 7.6°C. More variability is observed in summer than in winter. Summer temperatures fluctuate within a 4 to 6 C° band while winter temperatures are constrained within a 1 to 2 C° band.

3. Summer temperatures are about 5 C° warmer than winter temperatures. Mean summer temperatures peak in August and September (12 to 14°C); average maximum temperatures, however, peak in July and August (15.5 to 17.5°C). Winter mean temperatures are uniformly low (about 9.5°C) during the period December through March. Average minimum temperatures (7.5 to 8.3°C) generally occur in January.

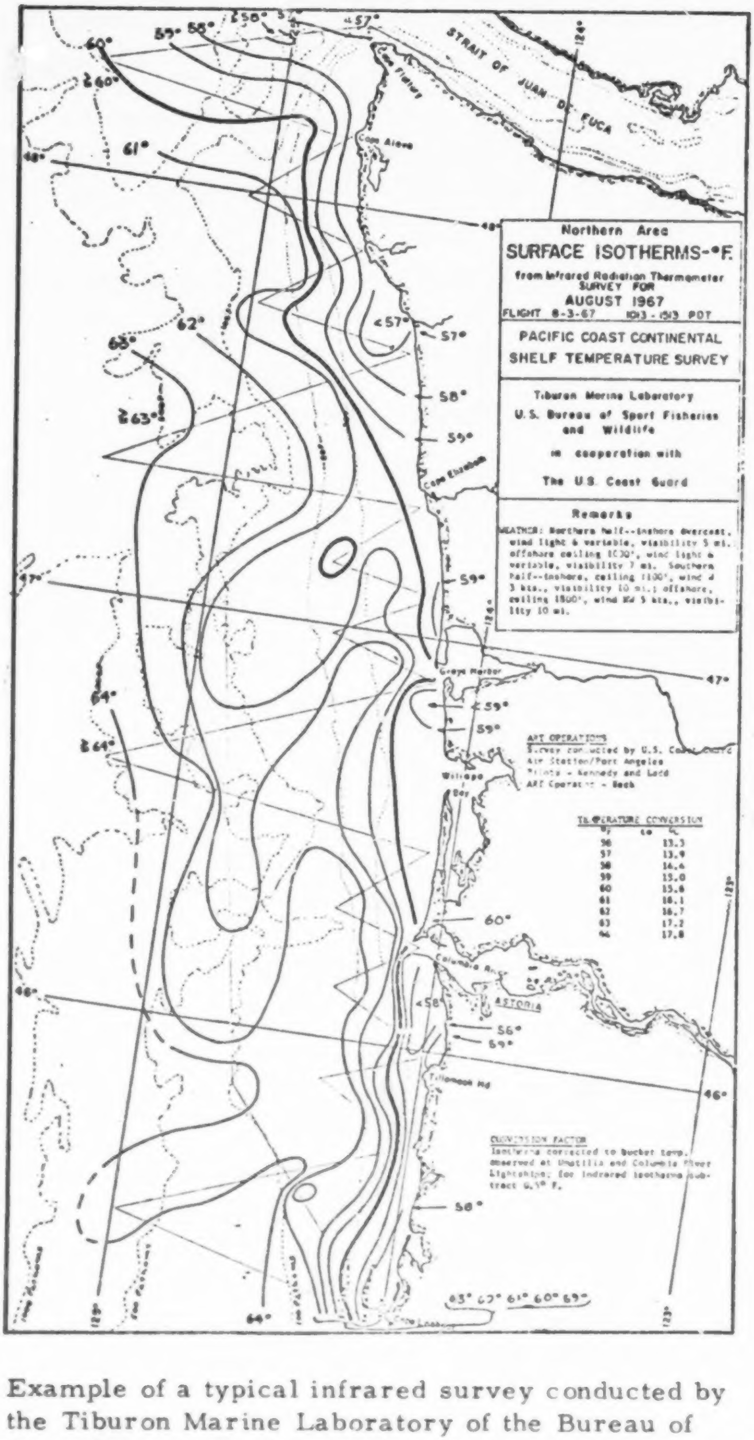
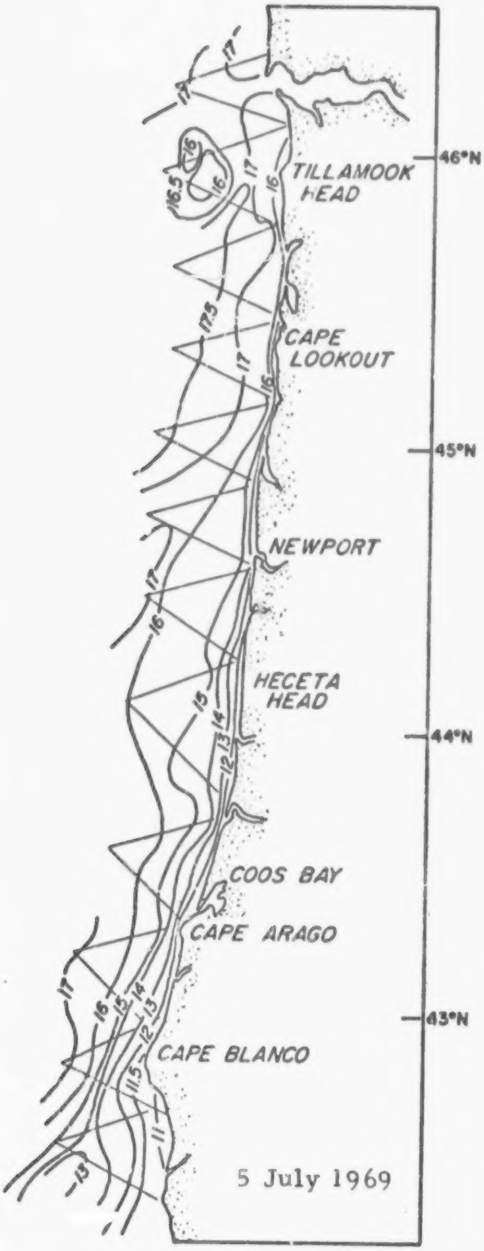


Figure 6-6. Example of a typical infrared survey conducted by the Tiburon Marine Laboratory of the Bureau of Sport Fisheries and Wildlife. Note that insufficient data prevents drawing temperature contours within 10 km of the coast.



5 July 1969

Figure 6-7. Temperature contours from a typical infrared survey conducted by Oregon State University's Sea Grant project "Albacore Central." Note closer spacing of flight track provides capability to construct contours closer to shore than that shown in Figure 6-6.

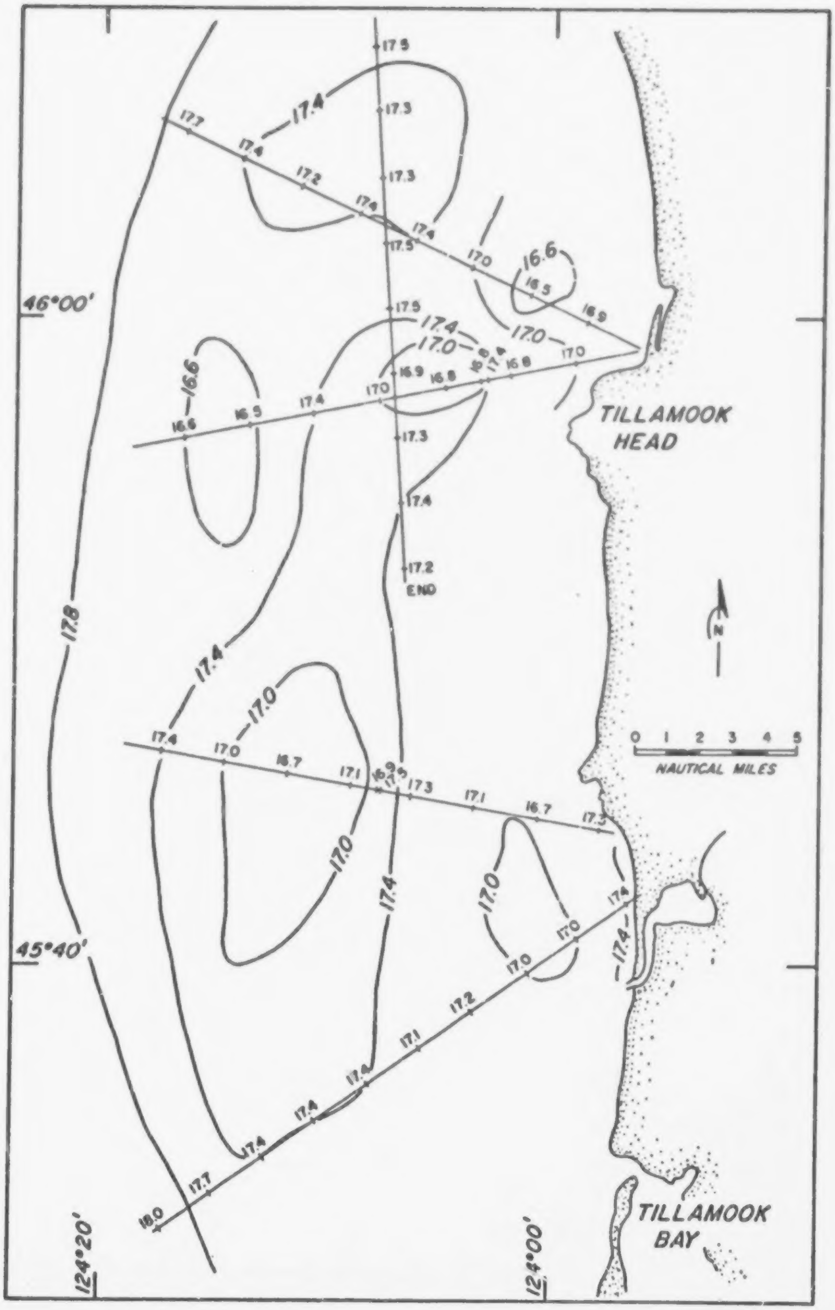


Figure 6-8. Segment of a typical infrared survey conducted by Oregon State University's Sea Grant project, "Albacore Central" (July 1969). Note that construction of temperature contours is highly subjective even for this relatively narrow strip. (Compiled by Burton W. Adams)

4. Summer temperatures in the northern portion of the area (from Willapa Bay, Washington, to Tillamook Bay, Oregon) are 2 or 3 C° warmer than temperatures observed at the more southerly stations. This is undoubtedly due to the warming influence of the Columbia River.

5. In areas where coastal upwelling is intense, summer temperatures are suppressed below those of the more northerly stations. Average minimum temperatures of 9.5 to 10.5°C are observed in upwelling regions whereas minimum temperatures of 12 to 14° are found in regions of little or no upwelling.

6. Due to extensive wind mixing of these shallow waters in winter, isothermal conditions exist from November through March-April.

7. Surface salinities are higher in summer (approximately 33.5‰) than in winter (approximately 32‰). Coastal upwelling tends to keep salinities elevated during the summer while winter rains and high river run-off tend to lower surface salinities.

8. Where coastal upwelling is prevalent, salinities in excess of 33.8‰ are frequently observed. However, during periods of weak or inactive upwelling, surface salinities may be reduced to 32.5 to 33‰.

9. In winter the discharge from the Columbia River flows north close to the Washington coastline. Mean salinities observed along the southern Washington coast are low (25 to 28‰) with maximum salinities rarely exceeding 30‰. During periods of peak discharge (June) salinities below 20‰ are not uncommon. During summer when the Columbia River plume flows offshore to the southwest, its freshening influence is still felt along the southern Washington coast. Surface salinities average about 30‰ occasionally reaching 33‰ in July and August.

Chapter 7. HEAT BUDGET

by Robert H. Bourke

Introduction

Rather than describe the climatology of the nearshore region, it was felt that a heat budget approach would be more informative.

A heat budget study for the coastal area of the Pacific Northwest has been completed by Lane (1150). He investigated the area from 40 to 50° North Latitude and from the coastline to 130° West Longitude. A further subdivision narrowed this area to include only the region within 60 nautical miles of the coastline. This subdivided region was established to provide a comparison between a coastal upwelling region and one free from the effects of upwelling. Measured values of sea surface temperature, wet and dry bulb air temperature, wind velocity, solar radiation, and cloud cover were used to compute the terms in the heat budget equation. The data used by Lane were from records of naval vessels for the period 1952-1962. These records are on file at the National Weather Records Center in Asheville, N. C. Each heat budget term was averaged month by month over a ten-year period (Table 7-1). The monthly variation of the total net heat exchange across the air-sea boundary was computed from the simplified heat budget equation: $Q_t = Q_s - Q_b - Q_h - Q_e$ 7-1

where Q_t is net heat transfer; considered positive when the sea receives heat energy,

Q_s is net short wave solar radiation incident on the sea surface,

Q_b is heat loss due to effective back radiation,

Q_h is heat conduction; considered positive when there is a net exchange of heat from the sea to the atmosphere,

Q_e is heat loss due to evaporation.

All terms are measured in langleys (calories/cm^2).

Empirical Methods

Direct measurement of terms in the heat budget equation (equation 7-1) is presently limited to laboratory experiments with the possible

Table 7-1. Ten-year average monthly values (langleys) for the major heat budget terms for a region where coastal upwelling is seasonally present. The Q_t overall includes this region as well as areas farther offshore not affected by coastal upwelling.

	Q_b	Q_h	Q_e	$Q_{s\ net}$	Q_t	$Q_{t\ overall}$
Jan	82	38	225	116	-229	-191
Feb	70	30	200	140	-160	-100
Mar	70	41	167	264	- 14	20
Apr	73	-10	118	423	242	198
May	63	- 5	129	486	299	277
June	72	- 7	150	528	313	304
July	51	-22	93	419	297	366
Aug	63	-15	100	447	299	274
Sept	75	-42	110	386	243	119
Oct	113	10	185	272	- 36	- 89
Nov	80	24	155	126	-133	-205
Dec	95	- 6	106	105	- 90	-203

(modified from Lane, 1150)

exception of the radiative terms. In practice, empirical methods are used to compute the heat budget terms. Spatial and temporal measurements of sea surface temperature, wet and dry bulb air temperature, wind velocity, solar radiation, and cloud coverage are observed from which diurnal, monthly, or annual means are computed. A variety of empirical relationships have been established for the computation of each heat budget term utilizing the above measurements. A discussion of the methods employed by Lane follows.

Monthly mean values of the total daily solar radiation incident on the surface of the earth, Q_s, were obtained from the U. S. Weather Bureau at Astoria, Oregon. These monthly means were corrected for latitude and cloud cover. The percent of the incident solar radiation reflected from the sea surface, i. e., the albedo, was determined by slightly modifying and averaging the albedos as determined by Burt (1116, 1117). The net solar radiation was calculated as the difference between the incident and reflected values. Monthly means of net solar radiation are listed in Table 7-1 and plotted in Figure 7-3.

The effective back radiation or the net loss of heat due to long wave radiation from the sea surface is a function of the surface water termperature and several atmospheric characteristics (temperature, vapor pressure, and cloud coverage). Lane used the relationship developed by Anderson et al. (1226) to compute Q_b.

$$Q_b = 1.141 \quad K_s^4 - K_a^4 [(0.74 + 0.025\ C\ e^{-0.0584h}) + (0.0049 - 0.00054\ C\ e^{-0.06h})\ e_a]\ 10^{-7} \quad \text{ly/day} \qquad 7\text{-}2$$

where K_s and K_a are, respectively, absolute sea surface and air temperatures in °K,

C is cloud cover in tenths, and

h is height of the clouds above sea level in meters.

The heat loss due to evaporation, Q_e, is primarily a function of the wind speed, V (m/sec), and the difference between the saturation vapor pressure and ambient vapor pressure, $(e_s - e_a)$.
A number of equations have been developed, but none are able to predict the evaporation from the oceans with great confidence or accuracy. The equation chosen by Lane originated with Sverdrup

(1191) and is of the form:

$$Q_e = 6.13\ V\ (e_s - e_a)\ \text{ly/day} \qquad 7\text{-}3$$

The conduction of sensible heat from the sea surface to the atmosphere occurs when the sea is warmer than the overlying air. Convective cells are created due to the instability within the air column resulting in cooling of the sea surface. If the air is warmer than the sea, a condition of stability is approached resulting in negligible exchange of heat. In general, the conduction process favors the removal of heat from the sea. The standard technique for estimating Q_h is by use of the Bowen ratio, i.e., $R = Q_h/Q_e$. Once the heat loss due to evaporation has been determined, Q_h can be found by

$$Q_h = \frac{0.61(K_s - K_a)\,Q_e}{(e_s - e_a)} \quad \text{ly/day} \qquad 7\text{-}4$$

where the terms are the same as those previously defined.

A comprehensive review of the heat budget including evaluation of the numerous empirical relationships, methods of data analysis, and techniques and equipment for obtaining the required meteorological variables may be found in several reports of which Edinger and Geyer (1229), Raphael (1180) and a TVA report (1131) are the most complete. Average monthly values of the heat budget terms for the Pacific Northwest may also be determined from the heat budget Atlas edited by Budyko (1114).

Discussion of Results

Over the ten year period of investigation the total net heat transfer varied considerably from one year to the next. The range was appreciable, varying from over 42,000 langleys gained by the sea in 1956 to almost 2,000 langleys lost by the sea in 1959 (Figure 7-1). Lane was able to show that annual fluctuations in both solar radiation and evaporation were the major contributors to the observed net heat differences.

From January through March the net heat transfer was negative indicating a release of heat from the ocean to the atmosphere (Figure 7-2). During March through May the direction of exchange reversed resulting in a warming of the ocean. During the summer the warming process continued at a relatively constant rate. However, farther offshore beyond the upwelling zone, the mid-summer atmospheric warming of the ocean decreased due to high surface temperatures

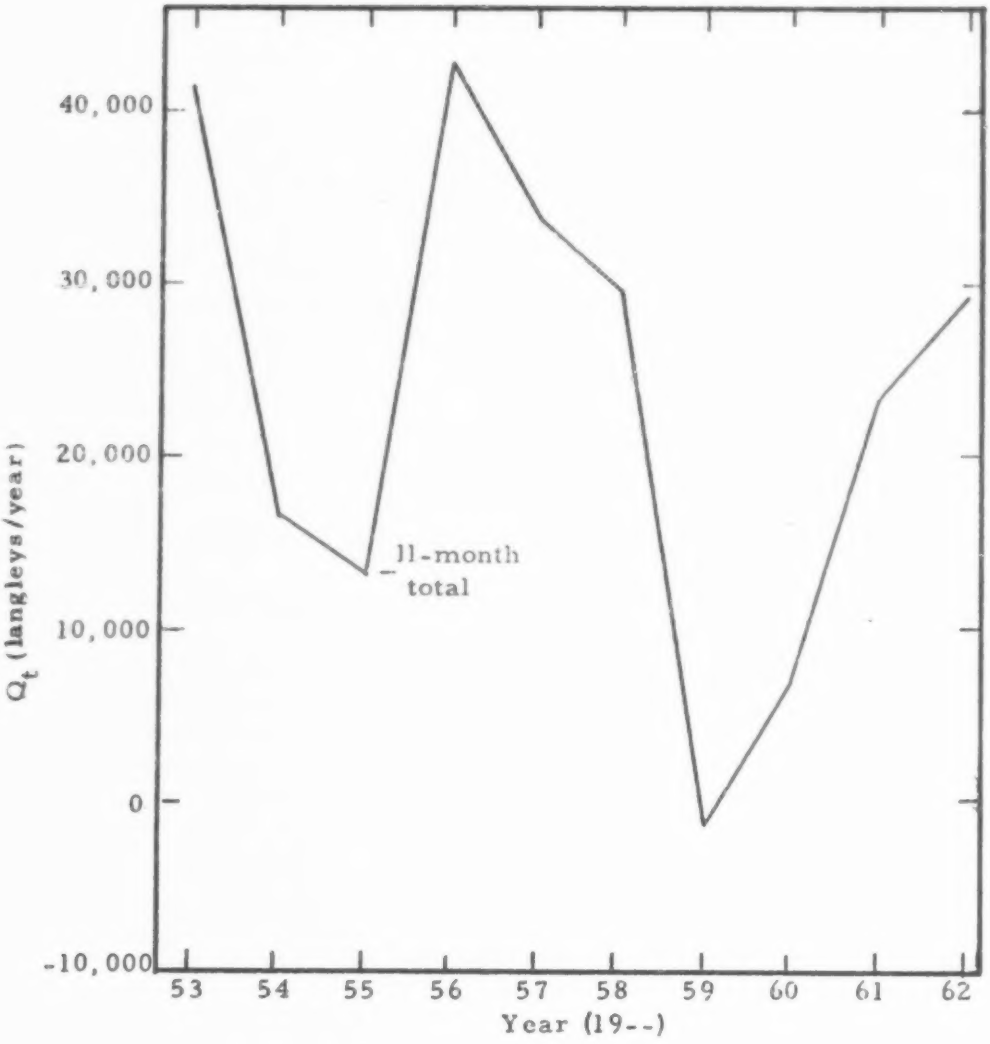


Figure 7-1. Variation of annual heat exchange (Q_t) from 1953 to 1962 for the region 40 to 50 N. Lat. and from the coastline to 130 W. Long. Note the extreme fluctuations in heat gained and lost by the region of the sea in 1956 and 1959, respectively (from Lane, 1150).

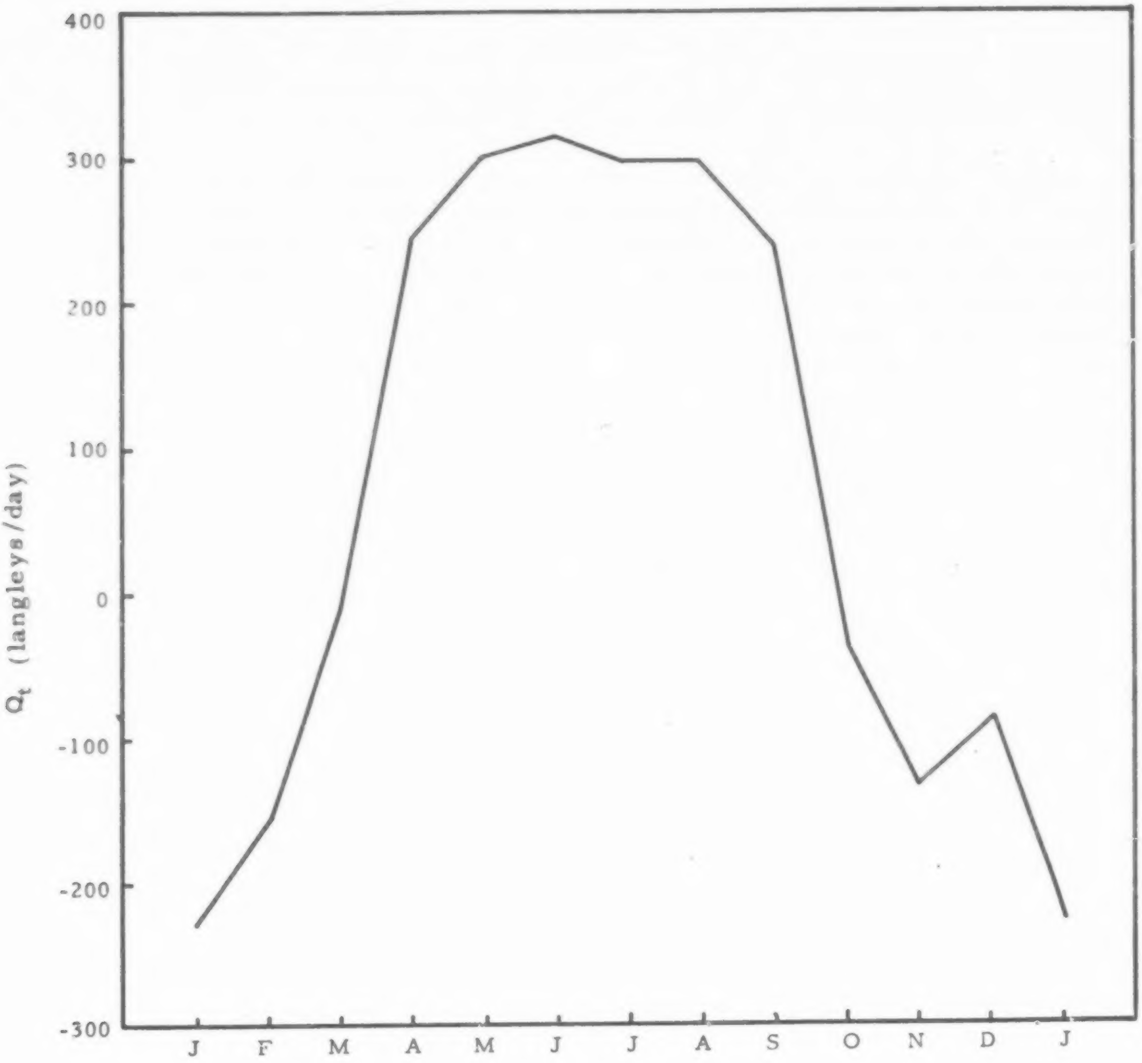


Figure 7-2. Monthly mean values of net heat transferred across the air-sea interface for the area from the Oregon coastline to 60 nautical miles offshore. From March through October net heat is transferred from the atmosphere to the ocean. (modified from Lane, 1150)

caused by warm Columbia River water and high values of cloud cover which reduced the incident solar radiation. By October the net heat exchange again reversed and the ocean continued to release heat at an increasing rate through December and January.

Net solar radiation and heat loss due to evaporation are the most significant factors affecting the total net heat exchange. The net solar radiation reaches its maximum during the summer months. April through September experience more than twice the insolation of the winter months (Figure 7-3). The heat loss due to evaporation is almost double that due to back radiation (Figures 7-4 and 7-5). However, during the summer months when upwelling is prevalent, the evaporative heat loss is suppressed from its winter maximum. The water transfer to the atmosphere during summer is less by approximately two inches per month compared to that in regions beyond the zone of upwelling. Cooling of the surface waters in summer due to upwelling also results in the conduction term, Q_h, being negative, i.e., a net conduction of heat to the sea (Figure 7-6). This lowering of the surface water temperature also results in a reduction of the effective back radiation during the summer months.

Direct Measurements

Direct measurements of net radiation and the evaporative and conductive heat fluxes will provide better knowledge of the heat transfer process across the air-sea interface. With increased understanding of the heat transfer process, the reliability of the empirical relationships should be improved. However, direct measurement of the heat budget terms is still limited to laboratory experiments with the exception of the radiative terms.

Solar radiation incident on the sea surface is usually measured with a pyrheliometer. Determination of the effective back radiation term is from empirical methods. The net radiation, both long and short wave, incident on the sea surface, however, can be measured with a net radiometer. Unfortunately, few of these devices are in operation at marine stations (1150).

Both the conductive and the evaporative heat exchanges can be expressed as the sum of a slowly fluctuating average value and a rapidly fluctuating random value. The slowly fluctuating portion is that which is estimated by empirical methods since these methods are based on average values of wind,

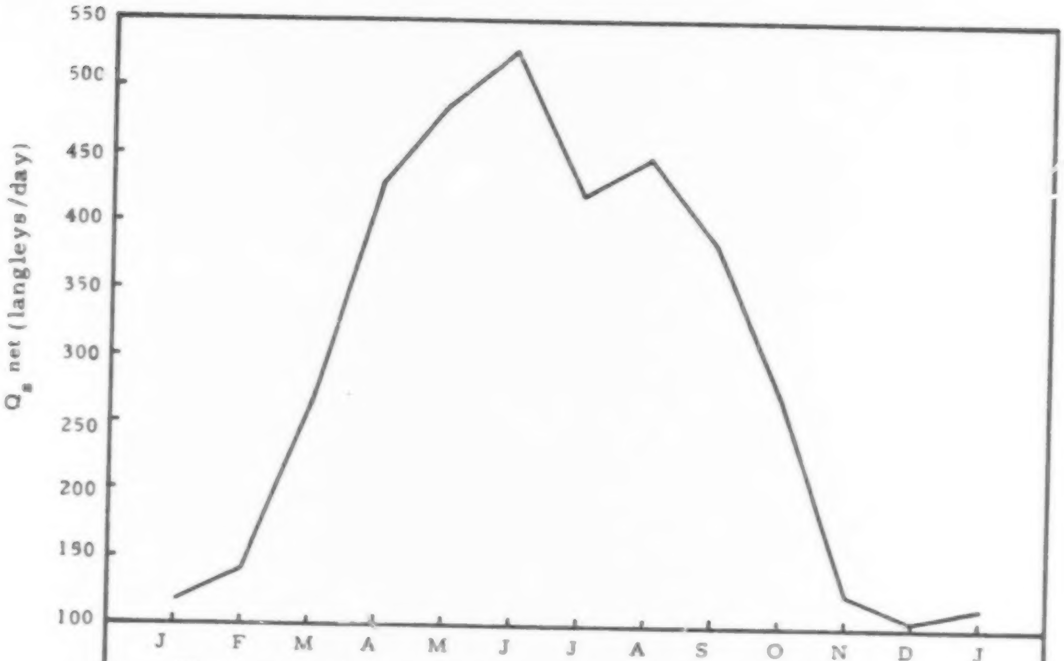


Figure 7-3. Monthly mean values of net solar radiation incident upon the area from the Oregon coastline to 60 nautical miles offshore. The summer months experience more than twice the insolation of the winter months. (modified from Lane, 1150)

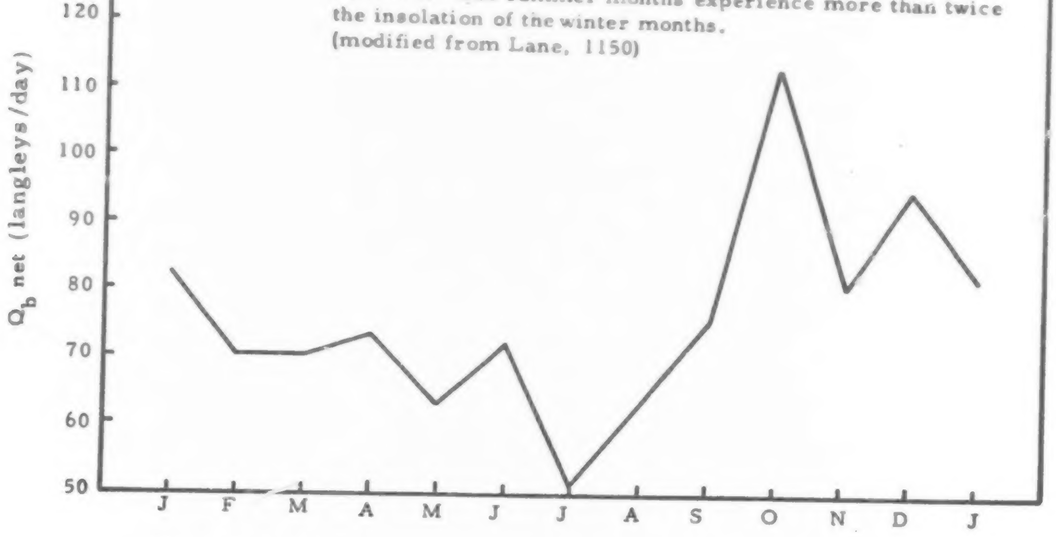


Figure 7-4. Monthly mean values of net back radiation for the area from the Oregon coastline to 60 nautical miles offshore. The low surface temperatures in summer resulting from coastal upwelling suppresses the net back radiation during this season. (modified from Lane, 1150)

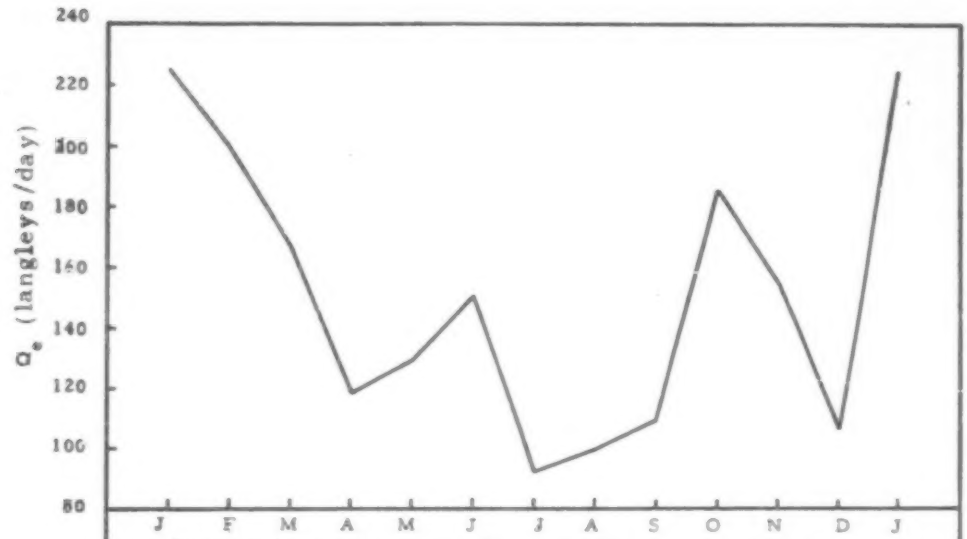


Figure 7-5. Monthly mean values of evaporative flux for the area from the Oregon coastline to 60 nautical miles offshore. In summer the evaporative heat loss is greatly suppressed from its winter maximum due to cooling effect of coastal upwelling. (modified from Lane, 1150)

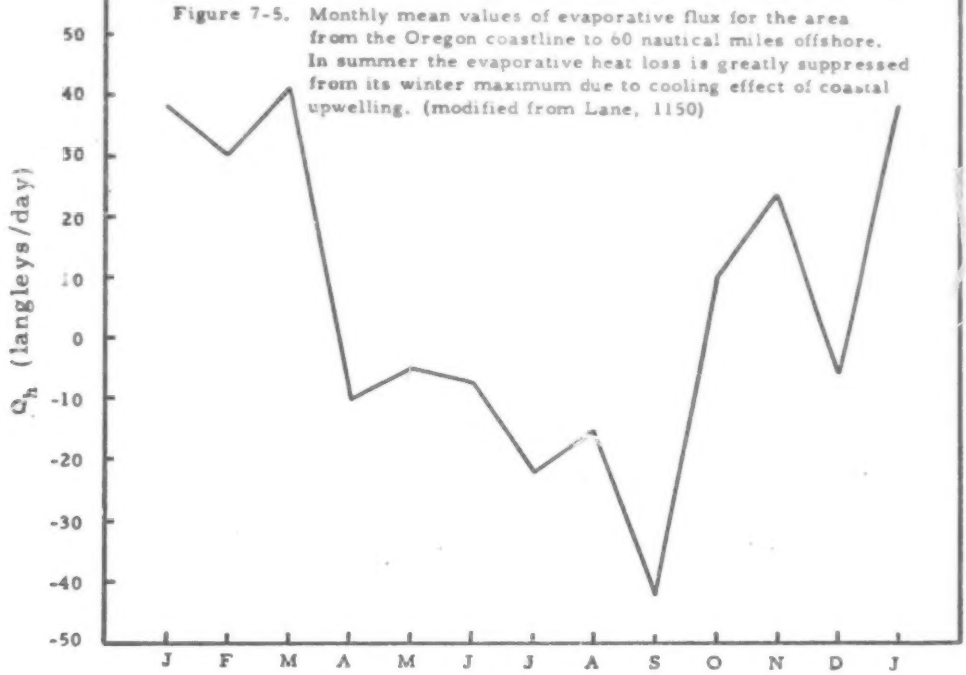


Figure 7-6. Monthly mean values of sensible heat conducted across the air-sea interface for the area from the Oregon coastline to 60 nautical miles offshore. Since surface temperatures are low in summer due to coastal upwelling, sensible heat is conducted from the atmosphere to the sea. (modified from Lane, 1150)

temperature, vapor pressure, etc. The rapidly fluctuating values are the fluxes of evaporation and sensible heat. These fluxes need to be measured to obtain the true picture of the evaporative and conductive heat transfer processes. In the past equipment with sufficiently fast response time to measure the rapid fluctuations was not available. Such equipment is now being developed in the laboratory. It will be some time in the future, however, before equipment reliability and cost will permit seasonal measurements encompassing a large area.

Summary

The direct measurement of the heat budget terms is generally limited to laboratory and field experiments. Empirical methods employing measurements of sea surface temperature, air temperature, humidity, wind velocity, solar radiation, etc. will have to suffice until direct reading instruments become available for practical use.

Based on empirical methods the following conclusions can be made concerning the heat budget for the coastal upwelling region off Oregon and Washington:

(1) The net heat exchange across the air-sea boundary varies considerably from year to year. In general, the sea receives a net annual input of heat from air-sea exchange.

(2) The factors most influential in altering the heat budget from year to year are variations in cloud cover, sea surface temperature, and wind speed.

(3) Coastal upwelling results in a lowering of air, sea, and wet bulb temperatures in the nearshore region. These reductions affect the heat budget by slightly reducing the back radiation, greatly reducing conduction from the sea to the atmosphere (conduction to the sea occurs frequently during the upwelling season), and greatly reducing the heat loss due to evaporation. Due to the relative magnitude involved, the reduction of the evaporative flux is the most important effect.

(4) The measurable effects of upwelling on the climate of coastal Oregon and Washington are a suppression of the summer and autumn air temperature values and an increase in relative humidity.

(5) Data are now available to construct heat budget forecasts on a regional basis. Such forecasts should be an integral part of any siting study for a thermal outfall.

Chapter 8. WAVES

by Robert H. Bourke

Introduction

The importance of wave statistics has long been recognized by oceanographers and ocean engineers as necessary for design of ocean and coastal installations. Good wave data, however, are rare and the records are often such that the wide variability inherent in waves may not be adequately described. The wave climate off the Pacific Northwest coast displays a definite seasonal pattern in response to the wind regime requiring wave records which encompass all the seasons.

The basic statistics required to describe the wave regime are the deep water wave direction, wave period and wave height. From these statistics one can determine the wave length, wave steepness, energy content, and particle motion. In the analysis of wave data the significant wave height and period (H_o and T_o) are calculated rather than average values. The significant height and period are the average height and period associated with the highest one-third of the waves observed or measured. In order to eliminate the shallow water effects of shoaling and refraction wave measurements or observations should be conducted in "deep" water, i.e., in water where the depth is larger than one-half the wave length.

The wave height, period and direction can be determined by observation from a moored ship in "deep" water, e.g., a lightship or instrumented buoy. The wave characteristics can also be inferred from observations of breaker height and period. Errors are inherent in both of these methods, but the chief difficulty lies in obtaining a complete annual record.

Wave statistics can also be calculated from the twelve hourly synoptic charts of the U.S. Weather Bureau. The fetch, duration, and velocity of the wind are determined and the wave characteristics are "hindcasted." Although this method relies heavily on one's ability to "read" or interpret the synoptic charts, it does provide a long and continuous record.

Data on wave height, period, direction, and frequency of occurrence over the yearly seasonal cycle are often important to power plant siting and design for several reasons. Some of these factors which are in part due to the wave climate are:

a) longshore current speed and direction
b) beach accretion and erosion
c) pressures and forces on bulkheads, pipelines, outfalls, etc.
d) dispersal of the heated effluent from the outfall by wave turbulence.

Measured or Observed Waves

In the Pacific Northwest few deep water wave observations exist for extended periods of time. One such set of observations taken at the Columbia River Lightship from 1933 to 1936 were analyzed and reported by M. P. O'Brien in 1961 (1164). The data were not obtained by trained observers and the methods used were rough, but O'Brien points out that the data are probably more accurate than most deep water observations since a limited number of observers on a relatively small anchored ship were used. The results are presented in Table 8-1.

O'Brien's analysis showed that the observed periods and wave lengths were less than the "correct" value. This conclusion was based upon comparative observations of the period of the breakers measured near the Columbia River mouth. O'Brien suggested that the reported wave lengths from the lightship should be increased by about one-third to bring them into general agreement with those observed on the coast. The predominant wave direction (as a function of the square of the wave height) was found to be from west to southwest (Table 8-2). In general, the observations show that the higher and longer period waves occur in winter (October through March).

Neal, et al. (1160) inferred the deep water wave statistics off Newport, Oregon, from observations on the beach of breaker heights and periods. The average value of the significant breaker height and period was determined from visual observations using the height of eye technique. From solitary wave theory the deep water wave height was related to the breaker height, H_B, by:

Table 8-1. Dimensions and periods of waves observed at Columbia River Light Vessel

	Percentage of total observations exceeding figure specified								
	20			50			80		
	H_o	L_o	T	H_o	L_o	T	H_o	L_o	T
	ft	ft	sec	ft	ft	sec	ft	ft	sec
January	8.4	310	8.9	5.3	187	7.2	2.9	68	5.6
February	6.6	280	8.4	3.8	130	7.0	1.9	82	4.8
March	8.4	326	9.5	4.4	242	7.5	2.5	159	6.1
April	4.5	227	10.0	2.7	112	7.5	1.3	65	4.8
May	6.2	252	7.9	3.9	172	6.4	2.1	88	5.0
June	5.7	192	7.6	3.3	125	6.0	1.3	71	4.2
July	4.4	275	9.0	2.5	178	6.7	1.2	45	4.0
August	6.1	193	8.1	3.6	168	6.1	1.6	134	4.1
September	6.4	238	8.1	3.8	180	6.5	1.8	78	4.6
October	7.9	293	9.5	4.9	210	6.9	2.4	110	4.6
November	9.9	296	8.5	4.8	223	7.0	2.7	177	4.3
December	10.6	325	9.2	6.3	239	7.2	4.0	153	5.5

H_c = wave height; L_o = wave length; T = wave period between crests.
(from O'Brien, 1164)

Table 8-2. Observed wave direction

Direction	Percentage of total observations over 12 months	Percentage weighted in proportion to H_o^2
N	0.73	0.57
NE	1.80	1.44
E	3.18	1.26
SE	2.38	3.30
S	15.02	25.14
SW	18.74	36.36
W	30.03	23.70
NW	16.57	8.24
Calm	11.54	-----

(from O'Brien, 1164)

$$H_o = \left[\frac{H_B{}^3 dl_s}{0.027\ L_o\ dl_o} \right]^{1/2}$$

where the refraction coefficient, dl_s/dl_o, was assumed close to unity and neglected. For the beach at Newport this assumption may not be valid due to the presence of both an offshore reef and physical barriers to the north and south which greatly influence the refractive pattern. The monthly averages of wave height, period and direction are listed in Table 8-3. The number of observations per month (from 3 to 9) permit only the most general conclusions to be drawn. The significant wave heights ranged from 2.8 ft. in August to 14.6 ft. in January averaging 7.2 ft. with the highest waves generated during winter (December through April). The significant wave periods ranged from 5.2 seconds in July to 17.8 seconds in February averaging 10.5 seconds for the year. The long period waves (11 to 12 seconds) occurred in winter from November to May. During the period September-April the direction of wave approach was from the west; in summer (May-August) they approached from WNW-NW.

The Coastal Engineering Research Center of the U. S. Army Corps of Engineers has established a program to measure wave data at various coastal sites around the United States (Darling and Dumm, 1125). The only site located within the study area is off the mouth of the Umpqua River where, in August 1964, a pressure type sensor was installed. Wave data from pressure sensitive devices can provide accurate information provided the pressure fluctuations can be properly converted to fluctuations of the sea surface. Recording is not continuous, however. The available records cover the periods of 13 August-13 September 1964 and 16 June-15 August 1966. No analysis has been made of these records as yet; pertinent wave statistics will be published as soon as the analysis is completed.

A prime source of deep water wave data is that measured from offshore oil rigs. These rigs are equipped with automatic wave recording instruments and have their vertical struts marked for visual observations as well. Several articles in industrial journals

Table 8-3. Monthly wave averages, Newport, Oregon, September 1968-August 1969.

	1968				1969							
	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.
Direction from	272°	276°	268°	277°	280°	271°	282°	283°	292°	297°	320°	324°
Period (sec)	11.4	9.7	12.5	11.5	10.5	11.8	12.3	11.3	11.6	9.3	9.8	7.4
H_o(feet)	6.8	7.5	7.0	10.4	9.0	8.3	8.3	8.4	6.1	5.2	6.6	4.5
No. of Obs.	3	6	7	5	6	8	5	8	7	9	9	4

(from Neal et al., 1160)

have reported the measurement of rather remarkable wave heights developed during intense winter storms off the Pacific Northwest coast. One rig survived a storm which generated 58-foot waves (Watts and Faulkner, 1220), only to be subjected to another even larger storm which generated a 95-foot wave (SEDCO 135F, 1188). Other large waves recorded from oil rigs are reported by Rogers (1183). None of these very large waves represent average wave conditions during a severe storm, but are simply the chance increase in wave height due to constructive interference from several large waves.

Hindcasted Waves

One of the most detailed wave studies for the Pacific Northwest region was conducted by National Marine Consultants in 1960 (1158) and 1961 (1159). Since equipment to actually measure deep water wave characteristics was not available at the time of the study, the investigators resorted to wave hindcasting techniques employing the spectral energy method of Pierson, Neumann, and James (1176). Wave prediction based on spectral theory is obviously not as accurate as prediction based on measured data, but it can provide indicative figures. The accuracy of the hindcast depends on the forecaster's experience and ability to interpret the synoptic weather charts produced by the U.S. Weather Bureau. The forecasters from National Marine Consultants had been making verified wave forecasts for four years prior to this study and were considered to be experienced.

The analyses of the deep water wave statistics were based upon meteorological records and charts for the years 1956, 1957, and 1958 which, when considered collectively, would represent an "average" year. The location of the four deep water stations shown in Figure 8-1 are:

Station 1	42°00'N,	125°00'W	(off Calif. -Oregon border)
2	44°40'N,	124°50'W	(off Newport, Oregon)
3	46°12'N,	124°30'W	(off Columbia River)
4	47°40'N,	125°00'W	(northwest of Grays Harbor, Washington)

The hindcasting method of wave forecasting has been shown to yield varied results based upon the individual judgments of the interpreters (Wiegel, pers. comm.). Because of this inherent variability in the results, the analysis by National Marine Consultants was considered to be too detailed for data based upon hindcasting techniques. Their

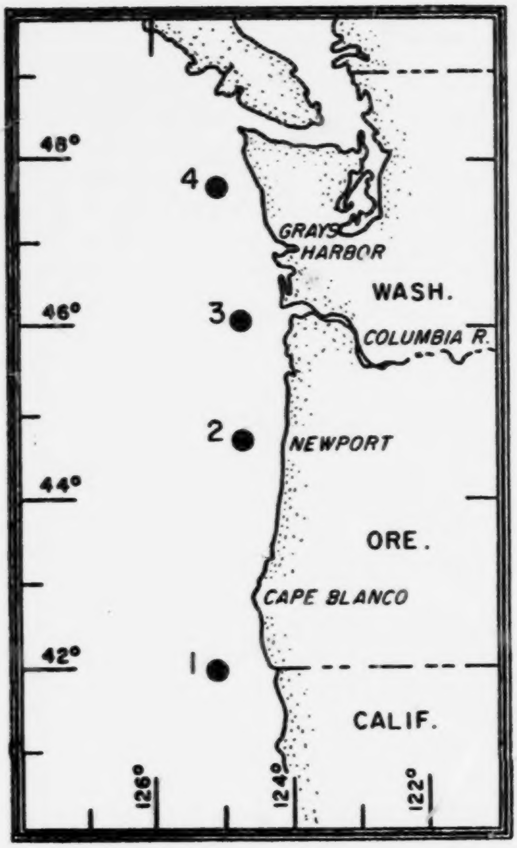


Figure 8-1. Location of deep water hindcast stations (from National Marine Consultants, 1159)

analysis has been made more general by grouping the data over four octants (N-NW, NW-W, W-SW, SW-S) and over four seasons (winter, spring, summer, fall). See Tables 8-4 and 8-5. The winter season includes the months of December, January, and February; spring - March, April and May; summer - June, July, August and September; and autumn - October and November. These groupings were based on the seasonal wind pattern of this region. The spring and autumn seasons are transitional periods between the more stable climatic seasons of summer and winter. A further generalization was to report only the average value of the significant wave height and period for each octant and season. The standard deviation (S. D.) of each is also presented to provide a measure of variability. In addition, the probable frequency of occurrence for each condition is shown.

The National Marine Consultants' report listed the data in terms of sea and swell, the former being local waves of a random nature located within the storm generation area and the latter being the more uniform waves which were generated from distant storms. Several different trains of swell may be present at the same time; only the height and period of the dominant swell train is reported. Calm periods are those times when no storm was present in the area to generate local waves or "sea." These periods also include the infrequent occasions when the direction of wave approach was offshore.

Analysis of the data listed in Tables 8-4 and 8-5 indicates that general conclusions may be drawn which are common to all four stations. The most important of these are:

1. The predominant direction from which the swell approached was from the NW-W octant during all seasons.

2. The predominant direction from which local seas approached was from SW-SSE during autumn and winter and from N-NW during spring and summer. The frequency with which the seas approached from a particular direction showed more variability than did swell.

3. Waves generated by local storms were generally higher than wave heights of swell.

4. The highest waves regardless of angle of approach always occurred in winter.

Table 8-4. HINDCAST DEEP WATER WAVE HEIGHTS (H_o) FOR THE OREGON AND WASHINGTON COAST

STATION	SEASON	TYPE	N - NW			NW - W			W - SW			SW - SSE			PERCENT OFFSHORE OR CALM
			H_o	S.D.	%	H_o	S.D.	%	H_o	S.D.	%	H_o	S.D.	%	
1	Winter	Swell	5.7	3.5	19.6	5.3	3.3	56.6	5.5	3.6	19.6	3.8	1.1	4.2	29.2
		Sea	4.1	2.4	15.0	5.3	2.9	8.1	6.5	2.8	13.7	8.2	4.9	33.8	
	Spring	Swell	2.9	1.2	15.7	4.8	3.3	65.8	2.7	1.4	13.4	3.3	2.2	5.0	26.9
		Sea	4.5	2.1	41.1	3.5	2.0	4.7	4.5	2.4	10.1	4.0	2.3	17.3	
	Summer	Swell	2.6	1.0	38.9	3.3	1.6	52.9	2.8	1.1	6.6	2.0	0.0	1.5	29.2
		Sea	4.8	2.6	59.5	3.0	1.1	2.8	3.3	1.5	3.9	3.2	1.4	4.7	
	Autumn	Swell	4.8	3.3	25.0	4.7	3.1	64.0	3.3	1.8	9.8	2.7	1.9	1.2	39.7
		Sea	4.6	2.6	27.4	4.3	2.1	5.1	4.2	2.0	9.9	5.0	2.8	18.0	
	Annual	Swell	3.7	2.8	24.8	4.7	3.2	59.4	4.2	3.2	12.7	3.3	2.0	3.1	30.3
		Sea	4.6	2.5	38.3	4.8	2.7	5.0	5.0	3.0	9.1	6.6	4.7	17.3	
2	Winter	Swell	4.5	2.7	10.1	5.4	3.7	52.2	5.2	3.6	24.7	5.6	3.9	13.0	30.1
		Sea	5.6	4.4	7.5	5.9	3.6	10.8	6.2	4.0	14.5	7.9	4.8	37.0	
	Spring	Swell	3.3	2.0	15.7	4.4	2.7	65.7	4.1	3.2	12.4	4.5	3.0	6.2	29.7
		Sea	4.0	2.2	32.6	3.9	2.3	9.6	4.6	2.6	10.4	5.3	3.3	17.4	
	Summer	Swell	2.9	1.7	33.3	3.3	1.7	59.5	3.2	1.4	4.4	3.5	1.3	2.8	29.5
		Sea	3.8	2.1	51.4	2.7	1.0	4.8	3.2	2.4	5.5	4.2	2.7	8.6	
	Autumn	Swell	4.8	3.2	17.8	5.1	3.6	68.4	3.7	2.5	7.1	3.8	2.6	6.7	35.3
		Sea	4.2	2.8	17.4	5.1	2.4	7.1	4.7	3.1	15.7	5.9	4.1	25.1	
	Annual	Swell	3.6	2.4	18.8	4.6	3.2	60.5	4.6	3.4	13.2	4.8	3.7	7.5	31.0
		Sea	4.0	2.5	30.0	4.7	3.2	7.[illegible]	5.0	3.3	10.6	6.5	4.4	20.8	
3	Winter	Swell	4.8	2.7	5.2	5.4	3.4	50.4	4.9	3.5	29.6	5.3	3.6	14.8	31.4
		Sea	5.6	4.0	5.1	7.0	3.9	11.7	6.5	3.9	13.9	8.3	5.0	37.9	
	Spring	Swell	3.3	2.0	11.5	4.3	2.6	63.7	3.8	2.4	16.3	4.1	2.7	8.5	32.1
		Sea	3.9	2.2	27.6	4.1	2.3	11.4	4.6	2.7	10.0	5.4	3.5	19.0	
	Summer	Swell	2.8	1.8	22.1	3.4	1.7	66.0	3.2	2.2	8.6	2.6	0.3	3.3	26.9
		Sea	3.6	2.0	44.3	3.0	1.6	10.5	2.9	1.6	7.4	4.6	3.3	11.0	
	Autumn	Swell	5.1	4.6	6.0	5.2	3.3	74.5	4.5	3.3	11.1	3.9	2.9	8.4	39.0
		Sea	5.0	3.0	12.8	4.9	2.3	8.0	5.8	3.2	15.8	6.3	4.2	24.6	
	Annual	Swell	3.3	2.5	11.1	4.5	3.0	62.4	4.3	3.2	17.4	4.6	3.4	9.1	31.6
		Sea	3.9	2.6	25.0	4.6	3.2	10.5	5.2	3.3	11.0	6.7	4.5	21.9	
4	Winter	Swell	4.1	0.7	0.5	5.4	3.4	46.9	4.5	2.8	33.1	5.0	3.3	19.5	24.8
		Sea	5.1	3.0	5.6	7.1	3.7	11.6	6.8	3.2	11.1	8.1	4.8	46.9	
	Spring	Swell	2.0	0.0	1.6	4.0	2.0	63.2	3.8	2.8	25.4	3.9	2.3	9.8	30.5
		Sea	4.1	2.2	22.2	4.7	3.0	14.5	5.2	3.1	10.1	5.4	3.4	22.7	
	Summer	Swell	3.2	1.4	3.1	3.3	1.8	72.7	2.9	1.5	18.1	3.3	2.6	2.5	23.9
		Sea	3.7	2.1	33.6	3.6	2.0	14.5	3.0	1.6	11.5	4.6	3.0	16.6	
	Autumn	Swell	---	---	---	5.4	3.5	73.0	3.9	2.9	17.6	4.3	3.3	9.4	30.2
		Sea	5.4	2.8	10.7	5.7	3.5	9.7	5.5	3.2	13.6	6.3	4.2	35.5	
	Annual	Swell	2.7	1.5	2.2	3.8	2.8	62.4	4.4	2.9	24.4	4.7	3.4	11.0	27.0
		Sea	4.0	2.5	20.0	4.9	3.4	12.9	5.0	3.4	11.3	6.7	4.5	28.8	

Table 8-5. HINDCAST WAVE PERIODS (T_o) FOR THE OREGON AND WASHINGTON COAST

			N - NW			NW - W			W - SW			SW - SSW			
STATION	SEASON	TYPE	T_o	S.D.	%	T_o	S.D.	%	T_o	S.D.	%	T_o	S.D.	%	PERCENT OFFSHORE OR CALM
	Winter	Swell	9.8	2.3	19.6	10.5	2.6	56.6	10.4	2.6	19.6	9.4	1.3	4.2	
		Sea	6.9	1.5	15.0	7.1	1.6	8.1	7.6	1.8	13.7	8.1	1.9	33.8	29.2
	Spring	Swell	9.9	1.7	15.7	10.5	2.4	65.8	10.2	1.8	13.4	9.4	1.6	5.0	
		Sea	6.9	1.3	41.1	6.2	1.1	4.7	5.9	1.4	10.1	6.8	1.6	17.3	26.9
1	Summer	Swell	9.9	1.4	38.8	10.3	2.2	52.9	9.3	0.3	6.6	11.0	0.0	1.5	
		Sea	6.9	1.7	50.5	5.6	0.7	2.8	5.9	1.1	3.9	5.9	1.1	4.7	29.2
	Autumn	Swell	10.2	2.2	25.0	10.5	2.5	64.0	9.5	1.4	9.8	9.3	0.5	1.2	
		Sea	6.9	1.6	27.4	6.7	1.5	5.1	6.7	1.5	9.9	7.1	1.6	18.0	39.7
	Annual	Swell	10.0	1.9	24.8	10.4	2.5	59.4	10.0	2.2	12.7	9.7	1.6	3.1	
		Sea	6.9	1.5	38.3	6.4	1.2	5.0	6.8	1.4	9.1	7.0	1.3	17.3	30.3
	Winter	Swell	10.0	2.3	10.1	10.7	2.8	52.2	10.2	2.7	24.7	9.4	1.7	13.0	
2		Sea	6.8	1.9	7.5	7.3	1.8	10.8	7.3	1.8	14.5	7.9	2.1	37.0	30.1
	Spring	Swell	10.3	1.8	15.7	10.7	2.6	65.7	10.5	2.0	12.4	9.1	1.8	6.2	
		Sea	6.3	1.4	32.8	6.2	1.3	9.6	6.6	1.4	10.4	6.8	1.6	17.4	29.7
	Summer	Swell	9.4	1.8	33.3	10.4	2.3	59.5	8.9	2.0	4.4	8.6	0.9	2.8	
		Sea	6.2	1.4	51.4	5.4	0.6	4.8	5.8	1.5	5.5	6.0	1.8	8.6	29.5
	Autumn	Swell	10.3	2.3	17.8	10.8	2.7	68.4	10.0	1.9	7.1	9.6	1.4	6.7	
		Sea	6.2	1.5	17.4	6.8	1.5	7.1	6.5	2.0	15.7	7.1	2.0	25.1	35.3
	Annual	Swell	9.8	2.1	18.8	10.5	2.8	60.5	10.4	2.4	13.2	9.4	1.5	7.5	
		Sea	6.3	1.5	30.0	6.8	1.7	7.8	6.8	1.8	10.6	7.3	2.0	20.6	31.0
	Winter	Swell	10.0	2.4	5.2	10.8	2.7	50.4	10.9	2.4	29.6	9.6	1.8	14.8	
		Sea	7.0	2.1	5.1	7.6	2.0	11.7	7.6	1.8	13.9	8.1	2.0	37.9	31.4
	Spring	Swell	10.0	1.8	11.5	10.8	2.3	63.7	10.3	2.0	16.3	9.1	1.6	8.5	
		Sea	6.2	1.5	27.6	6.3	1.3	11.4	6.5	1.4	10.0	6.9	1.7	19.0	32.1
3	Summer	Swell	9.4	1.6	22.1	10.2	2.3	66.0	9.7	1.8	8.6	8.2	0.5	3.3	
		Sea	6.0	1.3	44.3	5.6	1.0	10.5	5.6	1.0	7.4	6.6	1.7	11.0	26.9
	Autumn	Swell	10.1	2.3	6.0	9.6	3.2	74.5	10.6	2.4	11.1	9.6	1.4	8.4	
		Sea	6.8	1.6	12.8	6.8	1.4	8.0	6.9	1.6	15.8	7.2	2.0	24.6	39.0
	Annual	Swell	9.7	1.9	11.1	10.6	2.5	62.4	10.5	2.4	17.4	9.5	1.6	9.1	
		Sea	6.2	1.5	25.0	6.5	1.7	10.5	6.8	1.7	11.0	7.4	2.0	21.9	31.6
	Winter	Swell	9.6	1.5	0.5	10.5	2.7	46.9	10.9	2.7	33.1	9.7	1.8	19.5	
		Sea	6.7	1.5	5.6	7.8	1.9	11.6	7.6	1.6	11.1	8.4	1.6	46.9	24.8
	Spring	Swell	8.8	1.4	1.6	10.5	2.6	63.2	10.7	2.3	25.4	9.4	1.3	9.8	
		Sea	6.4	1.4	22.2	6.6	1.6	14.4	6.9	1.6	10.1	7.0	1.7	22.7	30.5
4	Summer	Swell	9.2	0.6	3.1	10.2	2.2	72.7	10.0	2.0	18.1	8.9	1.2	2.5	
		Sea	6.4	1.2	33.6	6.0	1.3	14.5	5.6	1.0	11.5	6.4	1.6	16.6	23.9
	Autumn	Swell	—	—	—	10.6	2.6	73.0	10.6	2.5	17.6	9.7	1.4	9.4	
		Sea	7.1	1.4	10.7	7.2	1.7	9.7	6.9	1.9	13.6	7.2	1.9	35.5	30.2
	Annual	Swell	9.0	1.5	2.2	10.5	2.5	62.4	10.6	2.5	24.4	9.6	1.7	11.0	
		Sea	6.3	1.5	20.0	6.7	1.8	12.9	6.7	1.8	11.3	7.4	1.9	28.8	27.0

5. Throughout the year the highest waves came from the SW-SSE octant.

6. The period of the swell was always greater than the period of the locally generated wind waves.

7. The shortest periods for both sea and swell occurred during summer.

8. The longest swell periods generally occurred during autumn; the longest sea periods occurred during winter.

9. Throughout the year the longest period swell generally approached from NW-W. At stations 2 and 3 long period swell also approached from the W-SW octant.

10. During all four seasons the longest period sea generally approached from the SW-SSE octant.

11. During all four seasons the periods of calm occurred with about the same frequency, 25-30%; the season of greatest calm was autumn.

Wave Steepness

Based on data from the National Marine Consultants' report (1159) for a station 20 miles west of the Columbia River, Ballard (1106) has calculated the wave steepness and its effect on sediment transport. The steepness of a wave is defined as the ratio of the wave height to its length (H_o/L_o) and is a critical factor in determining its capacity to move sediment (Saville, 1185). The steepness values computed from annual average conditions for both sea and swell were divided into three groups and the relative frequency of occurrence within each group determined for various wave directions (Table 8-6). Most of the swell (81.5%) fell in the H_o/L_o range of < 0.015 while local seas were dominant (90.3%) in the 0.015 to 0.025 range.

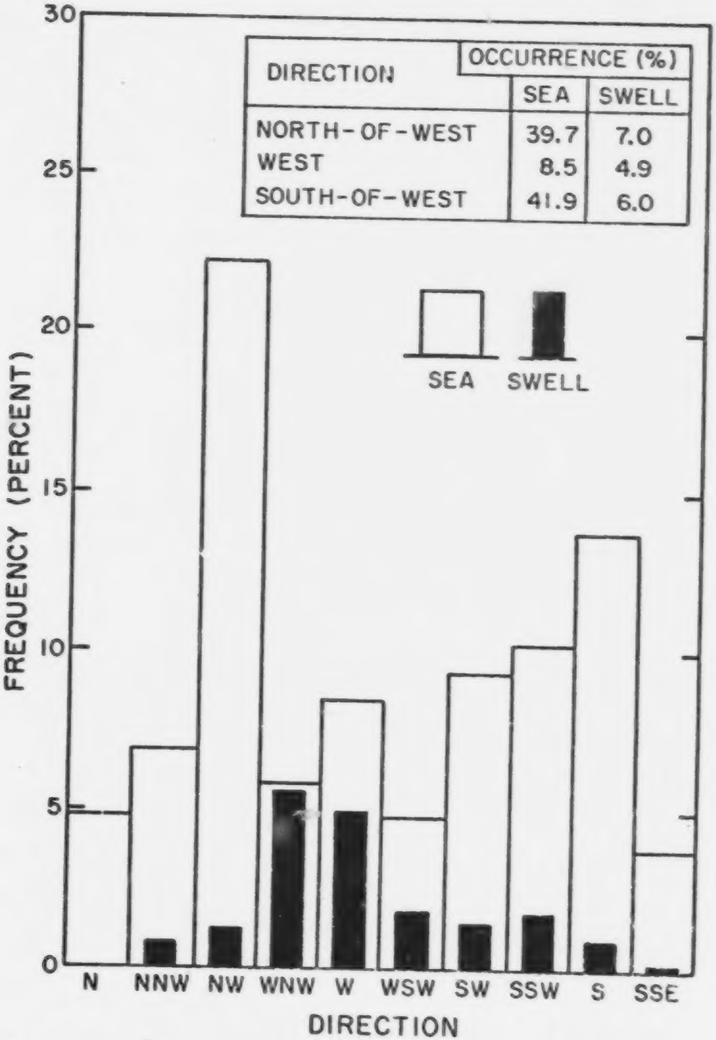
Waves with steepness values in the 0.015 to 0.025 range result in the greatest amount of sediment movement (1185). Ballard has plotted the relative frequency of waves in this range for various wave directions

Table 8-6. Relative frequency of waves with given steepness (H_o/L_o) values from various directions. Values represent average annual conditions for the years 1956, 1957, and 1958.

H_o/L_o	Condition	Percent occurrence from various wave directions										
		N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	Σ
<0.015	sea	---	---	---	---	---	---	---	0.1	---	---	0.1
	swell	---	0.6	9.0	24.2	26.4	10.2	4.7	4.0	2.3	0.1	81.5
0.015-0.025	sea	4.8	6.9	22.2	5.9	8.5	4.8	9.4	10.2	13.8	3.8	90.3
	swell	---	0.1	1.3	5.6	4.9	1.9	1.4	1.7	0.9	0.1	17.9
>0.025	sea	0.4	0.5	1.7	0.6	0.5	0.8	1.3	1.2	1.8	0.8	9.6
	swell	---	---	0.1	0.1	0.2	0.1	0.1	---	---	---	0.6

(from Ballard, 1106)

as shown in Figure 8-2. The predominance of local seas over swell in this range is evident. The inset of Figure 8-2 shows the effect of summing up the frequency of occurrence for both sea and swell from north-of-west and from south-of-west. The nearly equal frequencies of occurrence imply no net movement of sediment or a tendency to keep it localized.



DIRECTION	OCCURRENCE (%)	
	SEA	SWELL
NORTH-OF-WEST	39.7	7.0
WEST	8.5	4.9
SOUTH-OF-WEST	41.9	6.0

Figure 8-2. Relative frequency and direction of deep-water waves with steepness values of H_o/L_o = 0.015 to 0.025. All values represent average annual wave conditions. (from Ballard, 1106)

Chapter 9. COASTAL CURRENTS

by Robert H. Bourke and Bard Glenne

Introduction

Data on currents in the region of an ocean outfall are essential for the solution of heat dispersion problems. Measurements of current velocities in coastal waters are extremely sparse. Those measurements that have been made indicate that steady flow is not a common occurrence, but rather eddy flow and current reversals with tide or wind are more characteristic of the nearshore circulation. Defining the circulation patterns throughout the entire project region would be an enormous undertaking. A more efficient and practical approach would be to survey only those areas that could be classified as "prime" site locations. Detailed measurements made at these prime sites may allow extrapolation to other similar areas based upon a limited number of key measurements made in those areas.

Because of the many forces present to produce currents in coastal areas, current speed and direction are highly variable. Some nearshore currents have been found to respond to the changing forces on a time scale of about one hour (Neal, et al., 1160). Due to this variability average spatial as well as temporal values are usually reported. In regions where local topography influences the interaction of the driving forces the current may move as an eddy fluctuating widely in both speed and direction. For such areas average values may be meaningless. This is perhaps the reason why some offshore oil spills have been found to disperse in directions quite different from that predicted.

The primary forces that produce coastal currents are winds, main ocean currents, and tides. Of lesser importance are the current contributions from waves and pressure gradients.

Wind currents take place mainly on the surface. The extent of this surface layer is still under investigation, but recent studies indicate wind driven water motion to a depth of about 10 meters. Tidal wave motion is a so-called "shallow water" phenomenon and extends theoretically to the bottom of the oceans. Tidal currents, therefore, are generally thought to be essentially constant with depth in nearshore regions. Currents due to wind waves (swell) decrease logarithmically with depth and are essentially negligible at a depth equal to one-half the wave length.

Main Ocean Currents

The circulation of the main ocean currents off the Oregon-Washington coast is known only in general terms. The detailed circulation pattern is still a topic demanding extensive investigation. In general, the California Current is a broad, slow, and shallow southward flowing current. It flows offshore as a diffuse band about 300 miles wide with an average speed of 0.2 knots (0.34 ft/sec). It attains maximum strength during the summer when surface winds are consistently from North-Northwest.

The Davidson Current as reported by Schwartzlose (1186) is a seasonal northward flowing current attaining speeds of at least 0.5 to 0.9 knots over extensive distances. It has a minimum width of 50 miles. The current develops off the Oregon-Washington coast in September and becomes well established by January. Towards spring it diminishes and disappears by May. The driving force of the Davidson Current is not well understood. Off Oregon it appears to result from local wind stress (Ingraham, 1142), but Reid and Schwartzlose (1182) report it as not due to the local winds but to some larger scale phenomenon. Their direct measurements indicate support for the concept advanced by Sverdrup, et al., (1192) that the Davidson Current is a surface manifestation of a deeper northward flowing counter current that develops when the winds weaken seasonally.

Tidal Currents at Pacific Northwest Lightships

Coastal tidal currents found 5 miles (9 km) offshore, as observed by lightships along the Pacific Coast, are reported in the Tidal Current Tables (U.S.C. and G.S., 1202). The currents are rotary, turning clockwise, with a 12.5 hour period. Spring and neap tides, which occur biweekly, increase and decrease, respectively, the average tidal current by about 20 percent. Frequently, wind driven currents and other nontidal currents are of such strength as to completely mask the tidal current. These nontidal currents must be vectorially added to the tidal current to obtain the resultant current.

The tidal currents measured at the Blunts Reef Lightship off Cape Mendocino show very weak rotary characteristics with average speeds of less than 0.1 knots (0.17 ft/sec). At maximum flood the current sets north; at maximum ebb it sets south. The tidal current is generally masked by a nontidal current averaging 0.2 knots (0.34 ft/sec) setting towards the southwest from March to November and towards the northwest from November to March. The greatest observed velocity at the lightship is 3.0 knots (5.1 ft/sec).

The tidal currents observed at the Columbia River Lightship are also rotary, but rather weak, averaging about 0.3 knots (0.51 ft/sec). The set of the maximum flood and ebb currents are 020° T and 200° T, respectively. The discharge from the Columbia River completely masks the flood current at the lightship. The set of the nontidal current created by the river flow changes from SW (235° T) during February through October to WNW (295° T) from October to February in response to the seasonal wind pattern. The nontidal current speed ranges from a monthly average of 15 cm/sec (0.45 ft/sec) in March to 39 cm/sec (1.28 ft/sec) in June (Duxbury, et al., 1128). During periods of high river runoff the combined tidal and nontidal current frequently is 2.0 knots (3.4 ft/sec) or greater to the SW. The greatest observed velocity at the lightship is 3.5 knots (5.9 ft/sec). At the river mouth between the north and south jetties surface currents measured by the U. S. Army Corps of Engineers (1200) were 300 cm/sec (9.8 ft/sec) on ebb and 120 cm/sec (3.9 ft/sec) on flood during June. In September these values had changed to 240 cm/sec (7.3 ft/sec) on ebb and 180 cm/sec (5.9 ft/sec) on flood.

The tidal currents at the Umatilla Reef Lightship off Cape Arago, Washington are weakly rotary. Maximum currents occur 15 minutes after maximum flood or ebb is observed at the entrance to the Straits of Juan de Fuca. The average velocity of flood and ebb currents is 0.3 knots (0.51 ft/sec) setting 345° T on flood and 165 °T on ebb. Wind driven currents usually mask the tidal current. From November to April the flow is northerly (350 °T) at 0.7 knots (1.2 ft/sec) peaking to 1.0 knots (1.7 ft/sec) during December; from April to November the current is variable, generally setting SE at an average speed of 0.4 knots (0.68 ft/sec). The strong southeasterly winds of winter produce a combined current of 2 to 3 knots. The greatest observed velocity at the lightship is 3.3 knots (5.6 ft/sec).

Because changes in wind direction and speed may alter the wind driven currents, tables have been prepared to account for these changes (1202). Table 9-1 shows the increase in current speed due to increasing wind speeds. The number of degrees by which the wind driven current deviates to the right or left of the wind direction is listed in Table 9-2. This deflection of the wind driven current, as measured approximately 5 miles offshore, appears to be primarily due to coastline configuration rather than geostrophic effects.

Grays Harbor, Washington

A literature survey of this area conducted by the Oceanography Department of the University of Washington (1218) describes the average flood and ebb currents at the harbor entrance as generally onshore-offshore at 2.5 knots (4.2 ft/sec). Velocities in excess of 5.0 knots have been reported. The estimated velocity at a depth of 120-180 feet off the harbor entrance is 0.4-0.5 knots. The littoral current is generally northward although affected by the prevailing winds. In summer there is an occasional flow to the south with a maximum velocity of about 1.5 knots (2.5 ft/sec). The maximum velocity in winter when the flow is northward is about 4.0 knots (6.8 ft/sec).

Table 9-1. Average speed of current due to winds of various strength.

Wind velocity (mph)	10	20	30	40	50
Average current (knots) due to wind					
Blunts Reef	.2	.3	.4	.7	.8
Columbia River	.4	.5	.6	.8	.8
Umatilla Reef	.2	.6	.9	1.0	.9

Table 9-2. Average deviation of current to Right or Left of wind direction.

Wind from (in degrees)	Blunts Reef		Columbia River		Umatilla Reef	
	L	R	L	R	L	R
N		20		35		44
NNE		6		27		18
NE		10		9		34
ENE		32		29		48
E		28		17		52
ESE		7		2		38
SE	11		8			25
SSE		13	7			6
S		1	19		6	
SSW	11		44		13	
SW	18		74		32	
WSW	28		121		52	
W	60			145	77	
WNW		2		105	6	
NW		31		78		37
NNW		43		53		25

(from Tidal Current Tables, 1202)

Depoe Bay, Oregon

An extensive study was made of the nearshore water movement off Depoe Bay by Mooers, et al. (1156) from moored current meters and thermographs during August and September, 1966. Three arrays were anchored at 5, 10, and 15 miles off the coast (DB-5, DB-10, and DB-15). The current meters were spaced at a depth of 20 meters and 60 meters from the surface.

When the current speed and direction vectors for each recording time increment are progressively summed (tail of one vector placed against tip of preceding vector), a progressive vector diagram (PVD) results. PVD's for DB-5 (20m and 60m), DB-10 (20m), and DB-15 (60m) are plotted in Figure 9-1. Several conclusions can be drawn from these PVD's: (a) The flow at 20 meters is to the south, and at 60 meters is to the north; (b) The flow tends to follow the local topography, except for DB-15 (60 meters) where a strong onshore component is present; (c) There are frequent wiggles in the curves associated with tidal-like motions; (d) Periods of acceleration and deceleration in speed and reversals in flow direction are easily seen, e.g., at DB-5 (60 meters) the current changed direction three times within 20 days.

Table 9-3. Mean current measured off Depoe Bay, 15 August-24 September, 1966 based on a 10-minute sampling rate. S. D. is standard deviation.

Depoe Bay Station	Depth (m)	N (No. of days)	$\overline{U}$ (cm/sec) Mean±S. D.	$\overline{V}$ (cm/sec) Mean±S. D.	Scalar Speed (cm/sec) Mean±S. D.	Vector Mean	
						Speed (cm/sec)	Direction Deg. True
5	20	14.5	-2.1±11.4	-17.9±11.8	23.4±7.0	18.0	187
	60	35.4	2.7± 6.7	5.1±12.6	14.3±5.8	5.8	028
10A	20	37.1	-0.8±11.0	-13.6± 8.6	18.4±6.3	13.6	183
15	60	39.8	4.8± 7.6	3.9± 8.5	12.5±3.4	6.1	051

(modified from Mooers, et al., 1156)

A summary of the basic current data is presented in Table 9-3. The vector mean speed and direction at 20 meters depth, five miles off the coast, is 18.0 cm/sec (0.59 ft/sec) flowing southward (187°T). At 60 meters depth the mean vector speed has been reduced to a third of that at 20 meters and changed direction by almost 180° to 028°T. Histograms of current speed and direction and current velocity components for DB-5, 20 meters and 60 meters, are shown in Figures 9-2 and 9-3, respectively. These histograms are essentially unimodel indicating a predominance in velocity and direction.

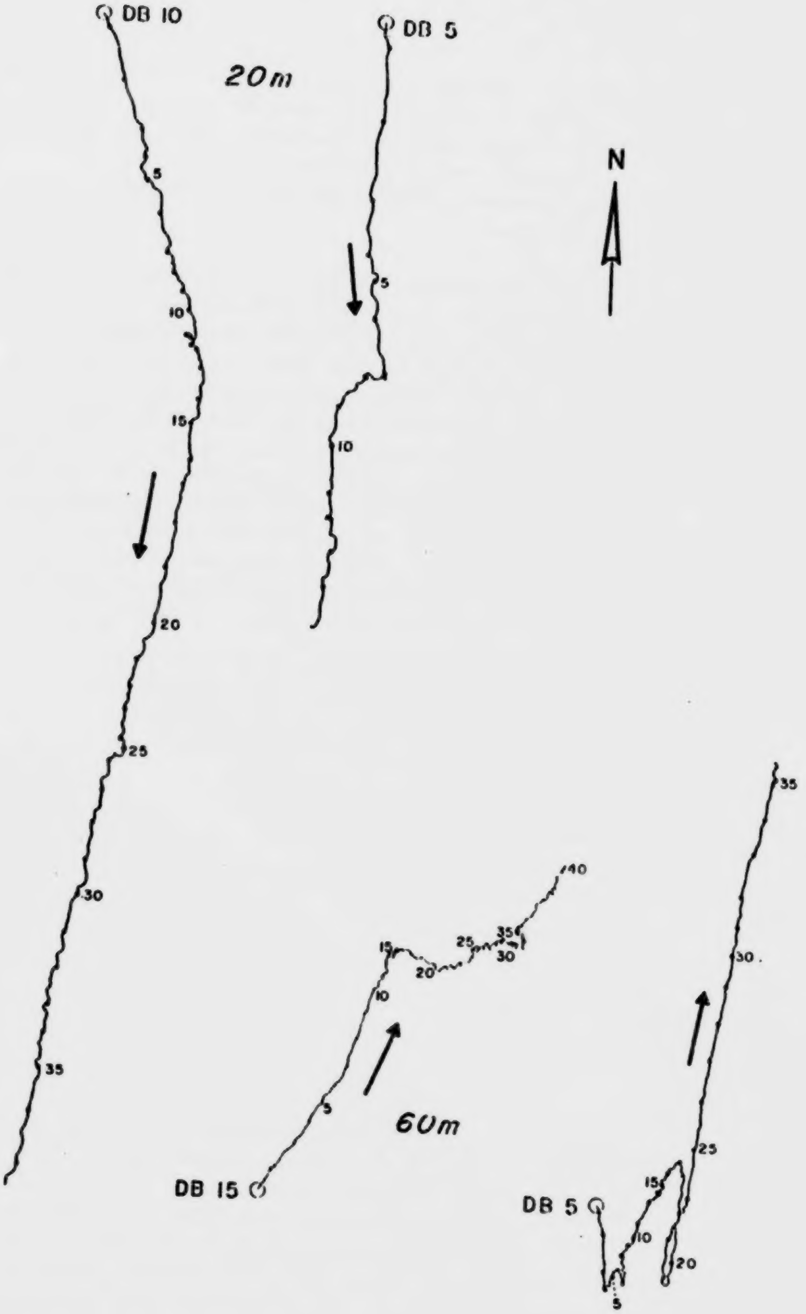


Figure 9-1. Progressive vector diagrams of currents, Depoe Bay array, 15 August-24 September 1966. The figures indicate the number of days since commencement of current meter recordings (from Mooers, et al., 1156).

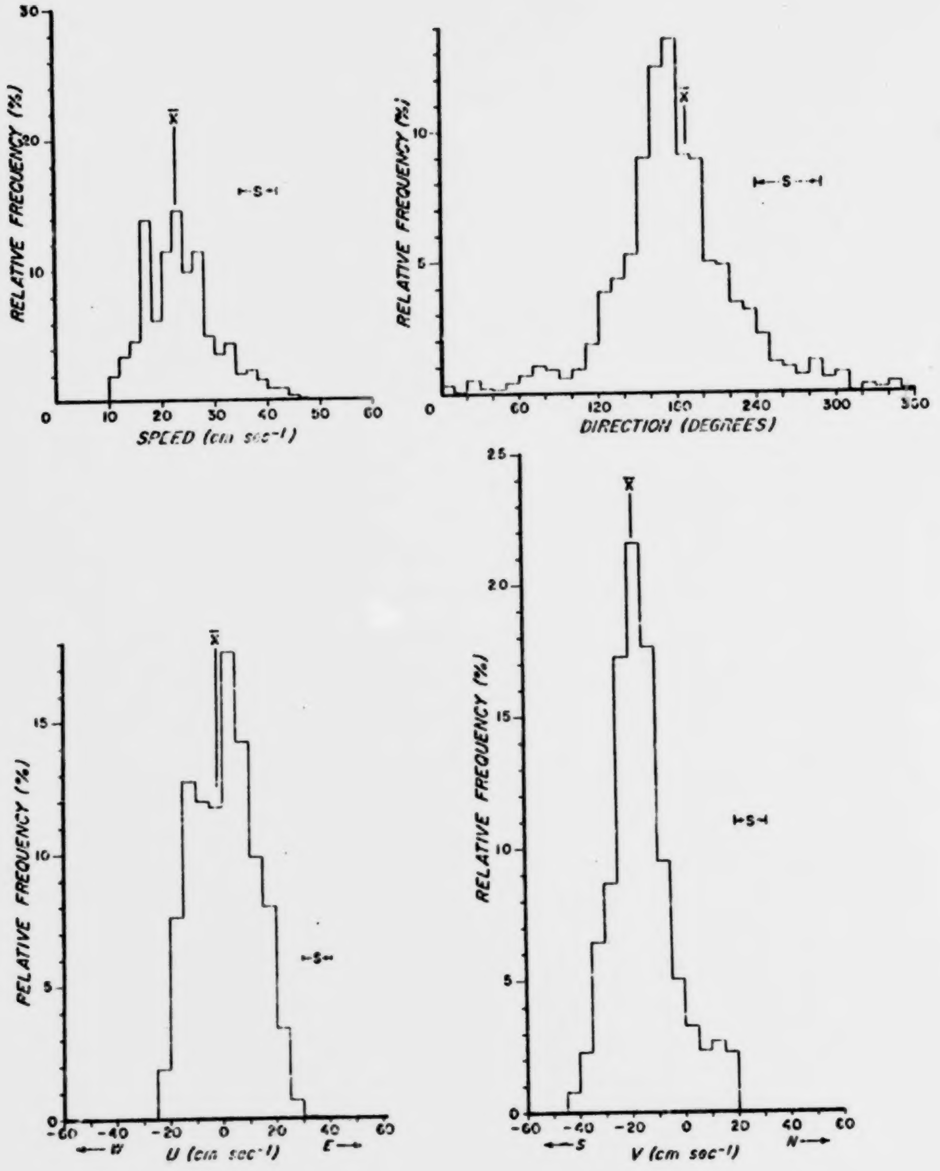


Figure 9-2. Histograms of current speed, direction, and velocity components measured 5 miles off Depoe Bay at 20 meters depth (from Mooers, et al., 1156).

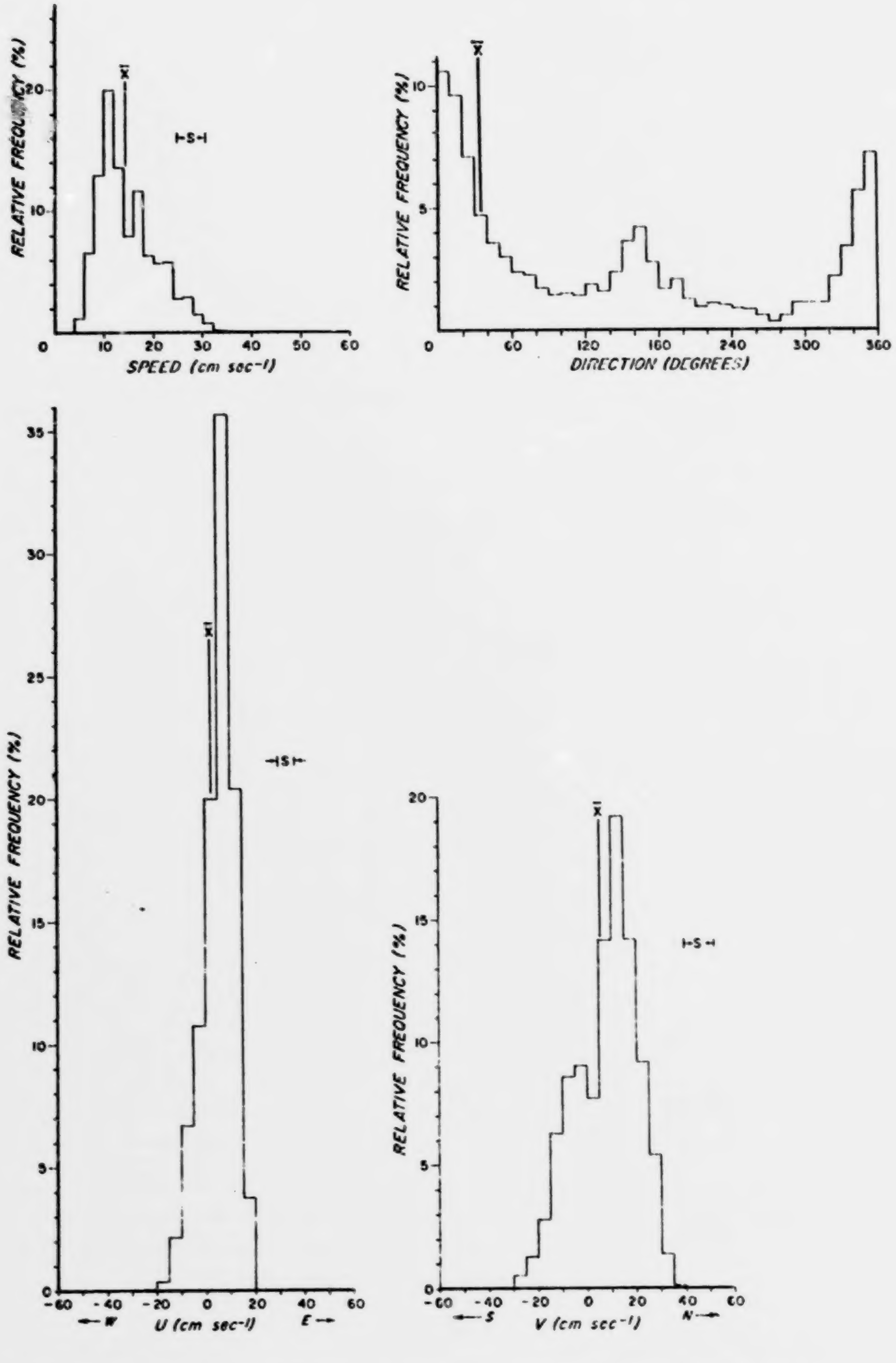


Figure 9-3. Histograms of current speed, direction, and velocity components measured 5 miles off Depoe Bay at 60 meters depth (from Mooers, et al., 1156).

In order to establish the vertical structure of the horizontal current, vertical profiles of current velocity were made at DB-5, 10, and 15 using a Savonius rotor current meter. These profiles, as drawn in Figure 9-4, show that at each station a subsurface minimum and a deeper maximum exist. No directions are given as these are single profiles and current direction is known to be highly variable over a tidal cycle. The speed minimum occurs at a depth near the base of the thermocline while the depth of the deeper maximum is associated with the base of the permanent pycnocline.

Additional nearshore current data is available from current meter arrays located off Depoe Bay and Yaquina Head during the summers of 1967 through 1969. Analysis and conclusions for the 1967 and the 1968 surveys are nearly complete (Pillsbury, Pattullo, and Smith, 1177). The analysis of the 1969 data is incomplete.

Newport, Oregon

A recent report by Neal, et al. (1160) discusses the currents near an ocean outfall off Newport. Due to topographic features (a shallow offshore reef, a prominent headland to the north, and a long jetty to the south) the currents are quite variable and unpredictable exhibiting the characteristics of a large eddy. The dominant driving force appears to be the wind, but many exceptions are noted. The current appears to deviate to the left of the wind direction for wind speeds less than 10 knots and to the right for wind speeds greater than 10 knots. South of Yaquina Head the predominant current direction was towards the beach. Near the ocean outfall off Newport the flow was either northeast or southwest. North of the jetties current flow was generally to the west.

Off Newport the littoral drift varies seasonally although the dominant yearly drift along the coast is believed to be north (Kulm, et al., 1761). From November-December to March the drift is northward reversing direction from April to October-November. Neal, et al. (1160), however, report from drift bottle studies that the longshore currents are definitely not sustained since at times the currents are in opposite directions at different portions of the beach. They found that the currents were about evenly divided between northerly flow and southerly flow throughout the year except during summer (June-August) when the waves were consistently out of the NW. Measured values of the longshore current velocity ranged from zero to over 1.6 ft/sec.

Additional current data is available from the work of James and Burgess (1146) who have used aerial photography and drift cards in plume dispersion studies off Newport. Surface current speed and direction can be calculated from this data, but at present no analysis has been undertaken for this purpose. Their aerial studies, however, do corroborate Neal, et al.'s findings that the outfall plume direction is quite variable and disperses in all directions.

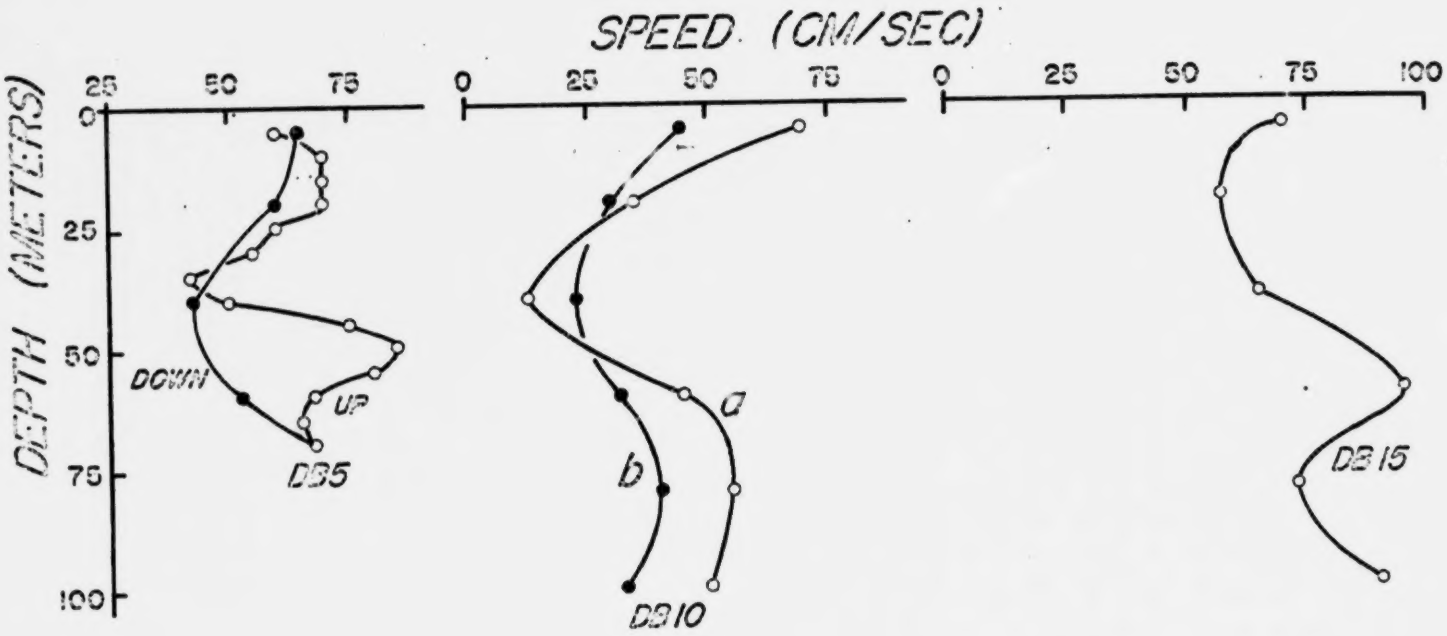


Figure 9-4. Vertical profiles of current speed 5, 10, and 15 miles off Depoe Bay, 23-24 September 1966 (from Mooers, et al., 1156).

Goodwin, Emmett and Glenne (1232) measured tidal heights and currents in the Yaquina, Alsea and Siletz estuaries. Higher flood velocities than ebb velocities were observed. In the Yaquina estuary entrance a maximum flood velocity of about 2.4 ft/sec was observed. Near Waldport in the Alsea estuary a maximum flood velocity of about 3.0 ft/sec was measured. Near Taft in the Siletz estuary entrance a maximum flood velocity of about 6.7 ft/sec was found. In all three estuaries an approximate 90° phase lag exists between tidal heights and tidal currents. No attempts were made to track the estuary flows offshore.

Coos Bay, Oregon

From a literature survey similar to that undertaken for Grays Harbor, Washington (1219), the average tidal current velocity is listed as 2.0 knots (3.4 ft/sec). Maximum ebb currents up to 7 knots (11.8 ft/sec) and flood currents of 3.5 knots (5.9 ft/sec) have been reported. The estimated velocity at a depth of 120-180 feet off the entrance is 0.4-0.5 knots. The littoral current is southerly in summer due to winds from the northwest and reversed in winter.

Trinidad Head to Eel River, California

From an investigation undertaken for the California Water Pollution Control Board, Humboldt State College has published a review of its oceanographic study of the nearshore area of Northern California (1140). The current pattern of this region is one of eddies superimposed on the California and Davidson currents. The headlands of Cape Mendocino and Trinidad Head, the jetties of Humboldt Bay, and the Eel River canyon all contribute to a mixed circulation pattern. Tidal currents, most pronounced near the entrance to Humboldt Bay, dominate the flow when other influencing factors are minimal. Nearshore currents have been correlated with wind conditions, but a lag effect of unstated duration was noted when the correlation was poor. Based upon a variety of observational methods, the current direction for each month from January to June (1959-1961) is presented in Table 9-4. Throughout this period the predominant observed direction was southward. Northward flow was observed most frequently during winter (January-February).

Table 9-4. Summary of observations of surface current direction for January-June, 1959-1961, between Trinidad Head and Cape Mendocino

Flow Direction	Jan	Feb	Mar	Apr	May	June	Total
South	27	20	23	24	28	24	146
North	33	15	13	18	7	11	97
West	3	1	1	0	0	0	5
East	5	2	2	2	1	1	13
None	1	0	1	5	0	1	8

(from Humboldt State College, 1140)

Bottom Currents

The scouring action and differential forces acting on structures and outfall pipes embedded in the ocean bottom are problems associated with near bottom currents (Brown, 1112). When current velocities are of appreciable magnitude, the bottom sediment may be loosely compacted with considerable material in suspension. Such conditions invite severe scouring and sedimentation near cooling water intake and outlet structures.

Direct measurements of near bottom currents are difficult to make and usually require special equipment. Few direct measurements are available. Observations along the Pacific Northwest coast have been made from sea bed drifters and moored current meters.

As reported in the section under Depoe Bay (1156), the direction of current flow measured at 60 meters (60 feet above the sea floor) was opposite to that measured near the surface (20 meters depth) (Table 9-3). At a point 5 miles off the coast for a period of 35 days during the summer the near bottom resultant current (vector mean current) was 5.8 cm/sec (0.19 ft/sec) at 028°T. The mean scalar speed was 14.3 cm/sec (0.47 ft/sec). Fifteen miles off the coast at 60 meters depth the resultant current was 6.1 cm/sec (0.20 ft/sec) at 051°T, an increase in the onshore component probably due to the increased depth. The mean scalar speed was 12.5 cm/sec (0.41 ft/sec).

Over the continental shelves of Washington and Oregon for water depths below 200 meters Dodimead, Favorite, and Hirano (1126) reported the current flow to be northward based on geostrophic calculations. This deep northward flowing current was corroborated by Ingraham (1142) who also employed the geostrophic technique.

The first direct measurement of the near bottom current off the Washington coastline was made by Gross, Morse, and Barnes (1137) using sea bed drifters, a saucer-like disk and stem arrangement which drifts a few meters above the bottom. Data analysis is essentially the same as that employed with surface drift bottles. Over the inner continental shelf (waters <40 meters deep) the flow was towards the coast apparently responding to the influence of waves and the ascending-shoreward motion of coastal upwelling. Speeds ranged from 0.7 to 2.5 km/day (0.03 to 0.09 ft/sec) averaging about 1.6 km/day (0.06 ft/sec). Within 10 km of the Columbia River mouth the flow was towards the river mouth at approximately 1.4 km/day (0.05 ft/sec). For shelf waters in excess of 40 meters depth the dominant flow was northward.

These measurements were made over a period of 3 years which indicates that these flows are persistent throughout the year. Seasonal variability in the flow of the near bottom current has not been determined.

The prediction of bottom currents may be calculated to an order of magnitude by investigating the relationship between current speed and the size of the sediment found on the sea bed. A review of previous investigations in this area and the development of a more general relationship is presented by Panicker (1171). For currents over a downhill slope he proposes

$$U = V_s / K\alpha \qquad 9\text{-}1$$

where U is the average velocity of the bottom current,

V_s is the average velocity of the sediment,

α is the bottom slope, and

K is the portion of available turbulent energy released by the suspended particle to maintain it in suspension; proposed to be of the order of 0.1.

A calculation of maximum depths where wave motion tends to move sediments is carried out in Chapter 3 in the section on Sediment Motion.

Current Flow under the Influence of Coastal Upwelling

During the summer months, June through September, the process of coastal upwelling occurs along the Oregon coast (Bourke, 1111). The north-northwesterly summer winds produce a southward flow in the surface layer and also an offshore surface flow due to the earth's rotation. This causes cold, saline water to upwell in eddies and form a rise in both the seasonal and permanent pycnoclines (Figure 9-5). The seasonal pycnocline (region of strong density gradients) breaks to the surface forming a surface front approximately 10 to 20 kilometers offshore. Shoreward of the surface front the waters take on the characteristics associated with upwelling -- relatively low temperatures, low dissolved oxygen content, and high salinities. Seaward of the surface front the surface temperature may be 5 to 7°C warmer than the surface waters in the upwelling region. Other indicators of upwelled water would be increased alkalinity, inorganic phosphate, and hydrogen ion concentration (Park, et al., 1172).

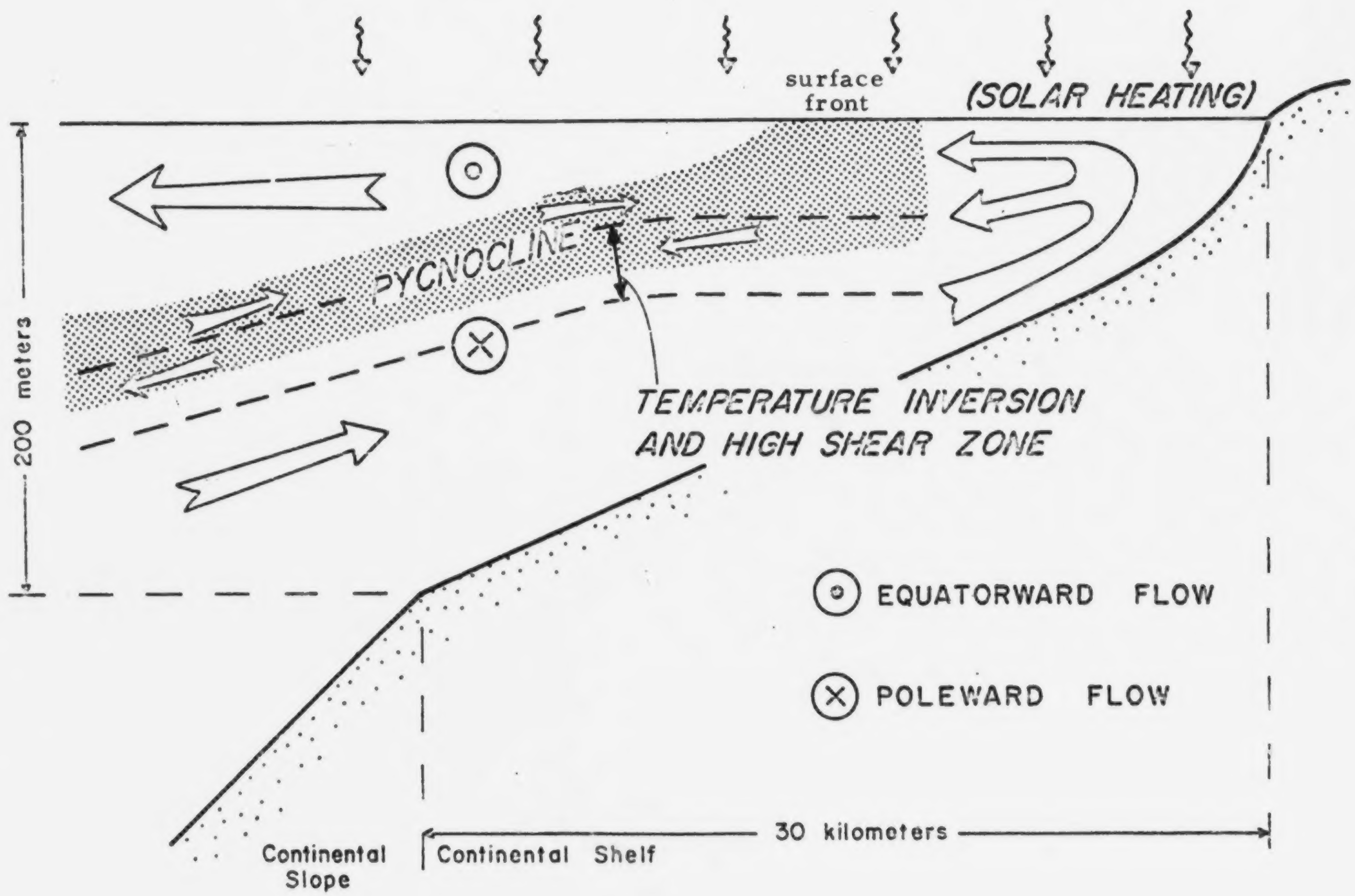


Figure 9-5. The mean current of the frontal zone in the coastal upwelling region off central Oregon (from Mooers, 1157).

The following summary of the general flow pattern for the coastal upwelling region off central Oregon during the upwelling season (Figure 9-6) is taken from that postulated by Mooers (1157).

1. The flow is southward in the upper 40 meters of the water column.

2. The flow is northward below 40 meters tending to concentrate beneath the inclined permanent frontal layer at about 100 meters.

3. The flow in the surface Ekman layer (a boundary layer in which frictional effects predominate in the equations of motion) is offshore. This transport layer is about 10 to 20 meters thick.

4. Within 10 to 20 meters of the bottom, the frictional effects of the bottom create a bottom Ekman layer where the flow is onshore.

5. Beneath the seasonal pycnocline (formed by summer heating and the influx of relatively fresh water from the Columbia River plume) the flow is offshore at a depth of 10 to 30 meters.

6. Within the upper portion of the permanent pycnocline from 20 to 60 meters the flow is onshore.

7. A new water mass formed near the surface possessing a characteristic temperature inversion sinks beneath the inclined permanent frontal layer and flows offshore in a layer at a depth of about 40 to 80 meters.

8. Between the above layer and the bottom Ekman layer the flow is onshore.

The process of coastal upwelling may go through the phases of inception, steady-state, and decay several times during the upwelling season since it is believed to be a process which responds to a wind field which is neither steady nor statistically stationary. Hence, these longitudinal and zonal flows fluctuate in depth and rate of transport commensurate with the current phase of upwelling.

The study of coastal upwelling undertaken by Mooers provides little information on the effects of the upwelling process for the region within 10 kilometers of the coast as the closest sensor was located

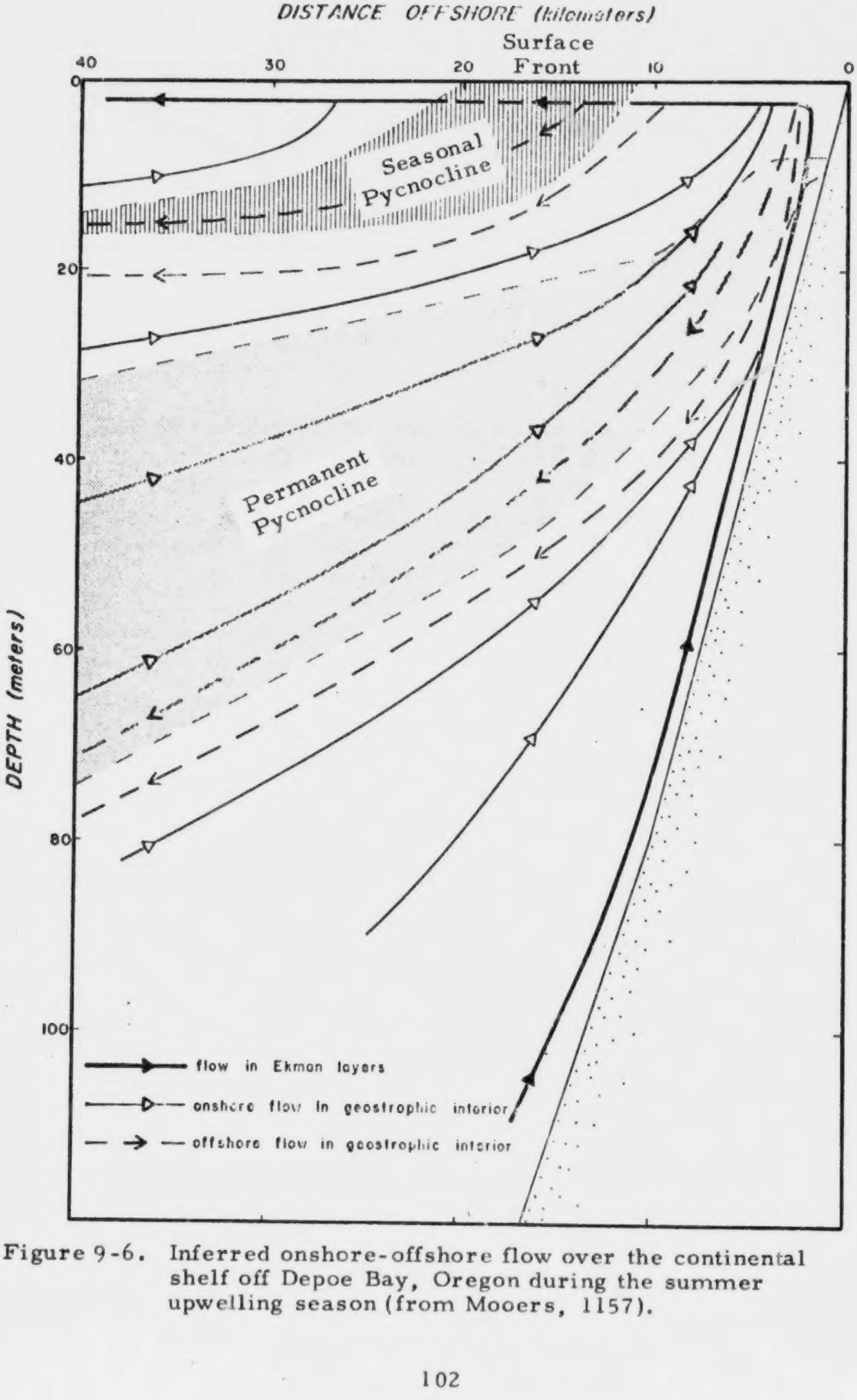


Figure 9-6. Inferred onshore-offshore flow over the continental shelf off Depoe Bay, Oregon during the summer upwelling season (from Mooers, 1157).

10 kilometers offshore. He states that during the period of observation it was uncertain how the upwelling process affected this region, but believed it to be a region where mixing is dominant.

Analytical Approach to Tidal Currents

In lieu of the scarcity of observed current data approximate analytical methods may be used to determine current velocities. One such method would be to consider only the wind and tide as the driving mechanisms for the establishment of coastal currents and to vectorially add the contributions from each of these forces.

(a) Wind Driven Currents

The drag of the wind passing over the surface of the water produces a drift current. Much of the initial investigation in this area was done by Ekman (1130). He found for a homogeneous body of water of infinite depth that the surface velocity of a pure drift current is proportional to the wind stress and, for an infinite ocean in the Northern Hemisphere, directed 45° to the right of the wind direction:

$$V = \frac{\tau}{\sqrt{\rho A f}} \qquad 9\text{-}2$$

where V is the surface current (cm/sec),

τ is the wind stress (dyne cm^{-2}),

ρ is the density of sea water (gm cm^{-3}),

A is the eddy viscosity coefficient (gm $cm^{-1}sec^{-1}$), and

f is the Coriolis parameter, $f = 2\Omega \sin\phi$ (sec^{-1}) where ϕ is the latitude and Ω is the rotation rate of the Earth.

For waters of finite depth the angle of deflection of the surface current from the wind direction is a function of h/D, the ratio between the water depth and Ekman's depth of frictional influence. In shallow water h/D decreases with increasing wind speed. Actual measurements have shown the deflection angle at the sea surface to vary between 25°-30° for low velocity winds (<4 m/sec) and approach the actual wind direction for high velocity winds (Neumann and Pierson, 1530).

One must use an "effective" eddy viscosity coefficient, A, which is a function of wind speed, i.e., A must increase with increasing wind speed. The following table (Table 9-5) for A as a function of wind speed is from Neumann (1161).

Table 9-5. Effective eddy viscosity coefficient as a function of wind speed.

Wind speed (m/sec)	4	6	8	10	14	18
A (gm/cm-sec)	58	161	332	577	1350	2520

Because of uncertainties in the values for wind stress and eddy viscosity coefficient, empirical formulae relating wind speed and current velocity directly have been postulated. These take the form

$$V = \frac{kW}{\sqrt{\sin \phi}} \qquad 9\text{-}3$$

where W is the wind speed in m/sec,

ϕ is the latitude, and

k is a coefficient which varies with wind speed; values used range from 0.76 to 2.59 (1530).

Wind drift currents and the relationship between wind speed and current speed at the surface have been discussed and studied, but few systematic measurements are available. Wide variability exists between actual measurements and that predicted by theory. Wiegel (1542) emphasizes that caution should be exercised when results based on theory are being used. Neither of the two preceding formulas consider the influence of a coast and should probably not be used in the nearshore region.

Bretschneider (1110) has developed a relationship between wind speed, U, and the steady state mean longshore wind-driven current, $\overline{V}_{st}$, over the continental shelf. Assuming shallow water conditions and constant values of $k = 3.0 \times 10^{-6}$ and $K = 10^{-2} \text{ft}^{1/3}$ for the wind stress and bottom stress parameters, respectively, the steady state mean current may be expressed as:

$$\frac{\overline{V}_{st}}{U} = 0.0173\, D^{1/6}\sqrt{\sin\theta} \qquad 9\text{-}4$$

where θ is the angle of the wind measured from the perpendicular to the coastline or bottom contours,

D is the water depth (ft), and

$\overline{V}_{st}$ is in ft/sec and U in knots.

Figure 9-7 shows the relationship of $\frac{\overline{V}_{st}}{U}$ versus D for various angles θ. Exact values for the wind stress and bottom stress parameters have not been established.

(b) Tidal Currents

An approximate tidal current velocity can be found from the information listed in the Tide Tables (1203) and the Current Tables (1202). The time it takes a particular stage of the tide (e.g., HHW) to travel from the Farallon Islands off San Francisco to Cape Alava off the northern Washington coast has been determined from the Tide Tables for four periods of the year. The pertinent data are listed in Table 9-6 along with tidal heights at HHW. The approximate distance from the Farallons to Cape Alava is 628 n. mi.

Table 9-6. Time of higher high water (HHW) and tidal height for four periods in 1969 for Farallon Island, California and Cape Alava, Washington.

	11 Feb		15 May		23 July		26 Oct	
	Time	Height (ft)	Time	Height (ft)	Time	Height (ft)	Time	Height (ft)
Farallon Islands	0459	5.8	2153	5.6	1659	5.8	1041	5.9
Cape Alava	0640	8.0	2340	8.5	1840	8.0	1228	9.3
Travel time (min)	101		107		101		107	

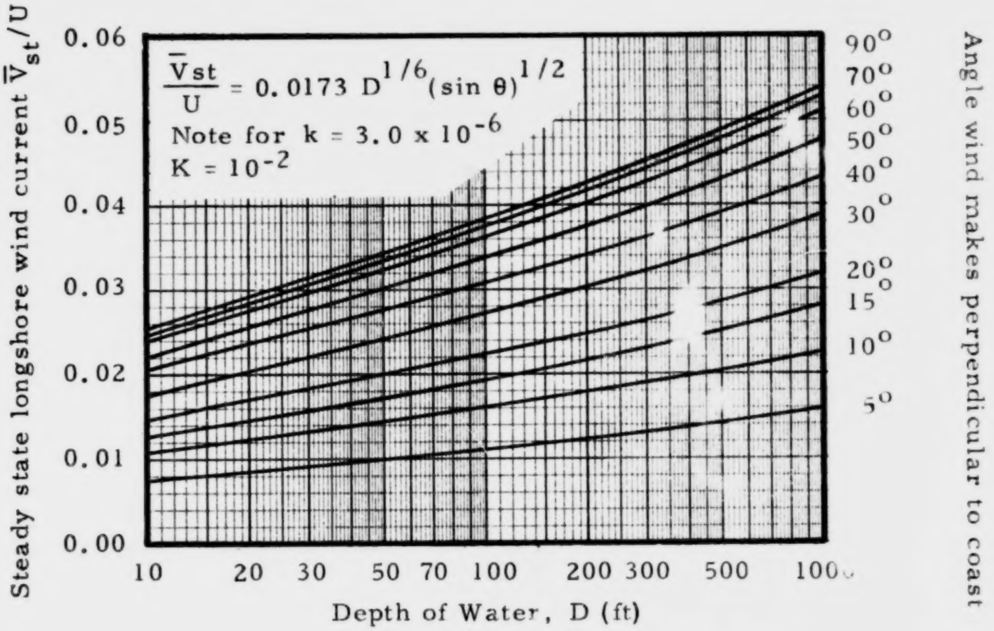


Figure 9-7. Relationship of $\overline{V}_{st}/U$ versus D for various angles θ. (from Bretschneider, 1110)

Using a travel time of 104 minutes, the velocity of propagation up the coast is 610 ft/sec (362 knots). The Current Tables indicate that the current is rotary but rather weak all along the Pacific Coast, setting approximately 060°T on flood, 240°T on ebb. Multiplying the computed wave velocity by the cosine of 60° yields the resultant wave velocity for a wave approaching the beach at an angle 30° normal to the shoreline of 305 ft/sec.

The maximum horizontal particle velocity or the maximum velocity of the net tidal motion is given by

$$u = g\ a/c \qquad 9\text{-}5$$

where u is the maximum horizontal particle velocity for a shallow-water progressive wave based on Airy wave theory (ft/sec),

g is the acceleration due to gravity, 32.2 ft/sec^2,

a is the tidal amplitude and from Table 9-6 is about $\frac{7.1}{2} = 3.55$ ft,

c is the wave velocity, 305 ft/sec.

The above values yield a maximum net tidal current of approximately 0.37 ft/sec (0.2 knots) approaching the coast from 240°T. This speed compares very favorably with that reported in the Current Tables based on measured values at lightships five miles off the coast (1202, p. 238).

Due to decreasing water depths as the tidal wave approaches shore, the wave speed decreases and the wave angle of approach becomes more and more parallel to the shoreline. The net onshore-offshore component of particle motion in this shallow coastal region can be computed from a simple tidal prism analysis. Assume that a flow of unit width perpendicular to the shoreline with period T and height H enters a tidal prism of volume ($L_{av}H$) in time T/2 (Figure 9-8). The average onshore-offshore particle velocity may be expressed as:

$$\bar{u} = \frac{2\ L_{av}H}{Td_{av}} \qquad 9\text{-}6$$

where d_{av} is the mixing layer thickness assumed to extend to the bottom.

The area between the sea surface and the bottom, $L_{av} \times d_{av}$, was calculated from the coastline to 3 miles offshore. This area was divided by the square of the water depth at 3 miles to yield the required L_{av}/d_{av} relationship in equation 9-6. Average net onshore-offshore tidal currents at selected areas along the Pacific Northwest Coast were computed using mean tidal heights from the Tide Tables (1203). These average tidal currents are listed in Table 9-7. Of primary interest is a comparison of the magnitude of these currents with location. The largest currents appear to occur in regions where the beach slope is relatively flat. The higher velocities of these regions implies better dispersion of the thermal plume. However, this advantage may be offset by the necessity of constructing a lengthy outfall to achieve the desired discharge depth.

Table 9-7. Average net tidal currents for the Pacific Northwest Coastline computed from tidal prism analysis.

Location	Mean Tidal Range (ft)	Average Onshore-Offshore Tidal Current (ft/sec)
Humboldt Bay entrance	6.2	0.08
Crescent City	5.1	0.12
Coos Bay entrance	5.2	0.05
Yaquina Bay entrance	5.9	0.06
Tillamook Bay entrance	5.7	0.05
Columbia River entrance	5.6	0.13
Long Beach, Washington	6.2	0.14
Grays Harbor entrance	6.9	0.25
Pacific Beach, Washington	6.5	0.13

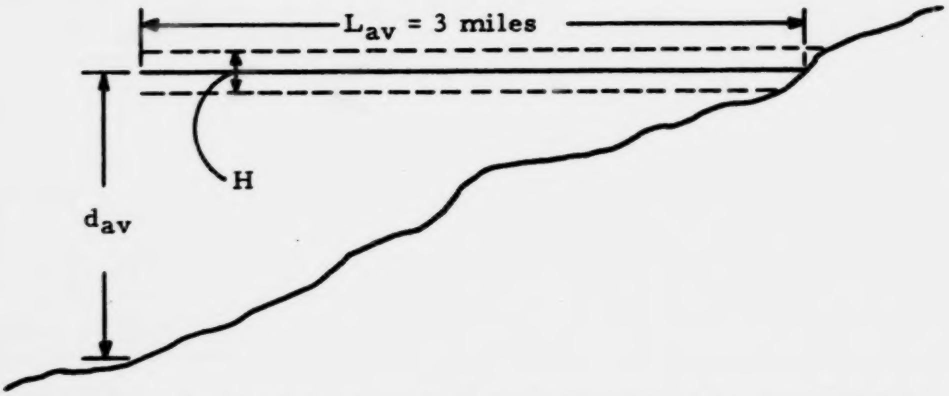


Figure 9-8. Sketch of tidal prism defining terms used in equation 9-6.

Longshore Currents

Most waves approach the coastline at an angle to the bottom contours. The effect of refraction tends to bend the angle of wave approach such that the wave crests are almost parallel to the shoreline by the time the waves break. However, when waves do break at an angle to the beach, the shoreward transport of water has a component parallel to the coast. This water motion parallel to the coast is the longshore current. These currents are the major mechanism of longshore sand transport. Most of the longshore sand transport takes place in the surf zone.

Longshore current velocities can be computed from the relationship listed by Eagleson (1129)

$$V_L^2 = 3/8 \left[\frac{gH_b^2 n_b}{h_b} \right] \left[\frac{\sin\alpha \, \sin\theta_b \, \sin 2\theta_b}{f} \right] \qquad 9\text{-}7$$

where V_L is the mean longshore current velocity (ft/sec) assumed to be constant in the surf zone. The current will actually decrease with distance from the shoreline as the depth increases;

H_b and h_b are respectively, the wave height (ft) and water depth (ft) at the point of breaking;

n_b is the ratio of the group velocity to phase velocity;

α is the beach slope;

θ_b is the angle between the breaker crest and the original wave crest;

f is the Darcy Weisbach resistance coefficient = $[2 \log_{10} \frac{h_b}{k_e} + 1.74]^{-2}$;

k_e is the equivalent sand roughness, ft.

H_b and h_b can be computed from solitary wave theory using

$$h_b = 0.667 \, (H_o'T)^{2/3} \text{ and} \qquad 9\text{-}8$$

$$H_b = 0.78 \, h_b \qquad 9\text{-}9$$

where H_o' is the deep water wave height considering the effects of refraction, i.e. $H_o' = K_r H_o$

where K_r is the refraction coefficient.

H_b and h_b can more easily be determined from Figure D-54 in the U. S. Army Coastal Engineering Research Center Technical Report No. 4 (1121). A sample calculation using conditions appropriate to the Pacific Northwest Coast follows:

Assume $H_o' = 8$ feet; $T = 10$ sec; $\alpha = 1°$; $\theta_b = 5°$; bottom sand roughness, $k_e = 0.0033$ ft.

then:

$$\left.\begin{array}{l} h_b = 12.3 \text{ ft} \\ H_b = \ \ 9.6 \text{ ft} \end{array}\right\} \text{ from eqs. 9-8 and 9-9}$$

$n_b = 0.95$ from linear wave theory tables

$$f = \left[2 \log_{10} \frac{h_b}{k_e} + 1.74 \right]^{-2} = 0.013$$

$$V_L^2 = \frac{3}{8} \left[\frac{32.2 \times (9.6)^2 \times 0.95}{12.3} \right] \left[\frac{0.0175 \times 0.0872 \times 0.1736}{0.013} \right]$$

$$V_L = 1.26 \text{ ft/sec.}$$

This is in agreement with measured values off the central Oregon coast as reported by Neal, et al. (1160).

Many attempts have been made to predict longshore current velocity. Galvin (1553) in 1967 reviewed the theory and available data. More recently Lonquet-Higgins (1554) has suggested using the concept of radiation stress to more satisfactorily estimate the momentum of the incoming waves. However, the chief difficulty in estimating longshore current velocity is the inability to accurately measure the wave angle of approach.

Chapter 10. FIELD STUDIES OF THERMAL DISCHARGES

by Robert H. Bourke and Burton W. Adams

In the early nineteen sixties, several U.S. West Coast power companies initiated temperature studies of thermal power plant cooling water discharges. Important contributions to West Coast field studies of thermal discharges are described in the following paragraphs.

In 1962 Squire (1538), using an airborne infrared radiometer, measured the distributions of surface temperatures around the outfalls of four steam-electric plants in Southern California (Figure 10-1). The overflights, made on 16 January and 4 February, revealed increases of 4 to 20F° above ambient surface temperatures. The temperatures recorded in February were lower because the area had experienced storm conditions following the January survey. He concluded that the high surface temperature gradients indicated the existence of a warm water lens on the surface.

The Pacific Gas and Electric Company (PG&E) has conducted temperature surveys for a number of years at several of their thermal power plants in Central and Northern California. Early studies in 1950-1963 were made from surface craft using standard oceanographic instrumentation. These surveys were considered inadequate because the large distance between sampling stations and the time lag between successive measurements prevented rapid temperature changes from being accurately mapped. From 1963 to 1967 airborne infrared radiometers were used by PG&E to map surface temperatures around power plant outfalls.

Cheney and Richards (1507) examined the temperature outfall data from three power plants--Morro Bay (an open coast), Contra Costa (an estuary), and at Humboldt Bay (an enclosed bay). Their data are presented as maps of surface temperature (Figure 10-2a) and area-temperature profiles (Figures 10-2b and 10-2c). The infrared measurements were continuously supplemented with surface temperatures taken from a boat to provide calibration and temperature-depth profiles. Cheney and Richards concluded that the warming effect from power plant discharges, whether into a sea, a bay, or an estuary, is undetectable beyond a mile from the outfall. At 1,000 feet from the outfall the data showed only an occasional temperature exceeding 5F° above ambient. Subsurface temperature measurements in the

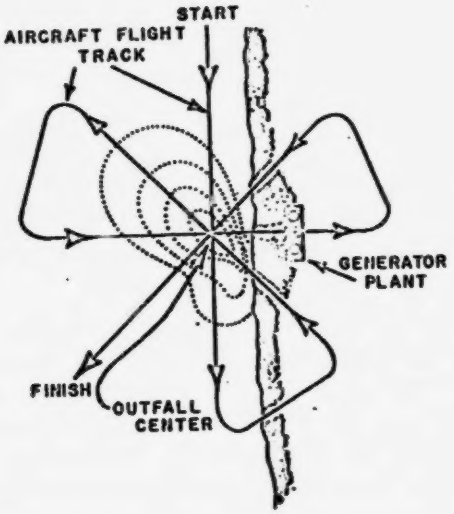
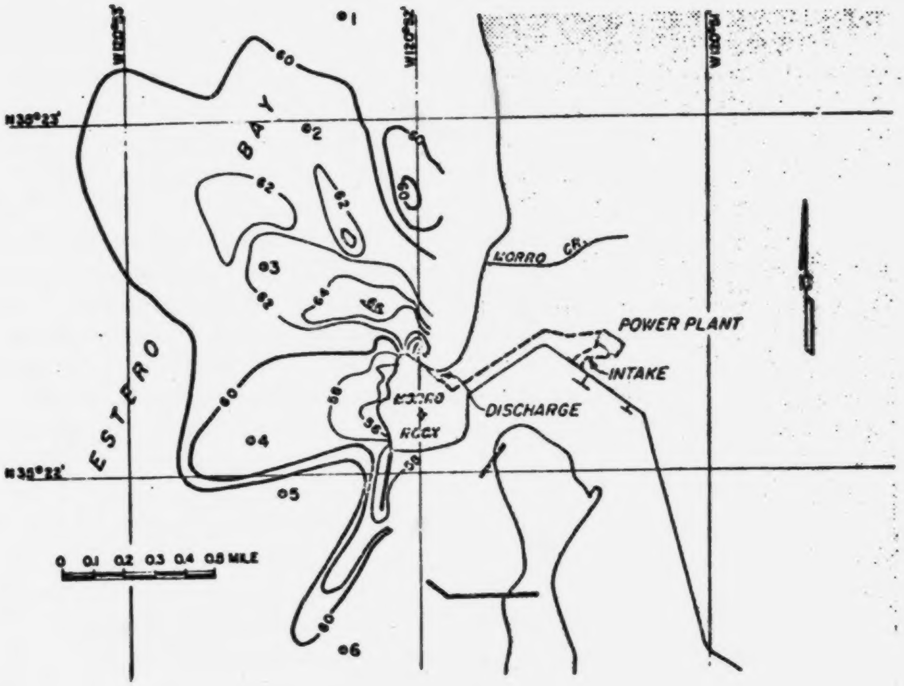
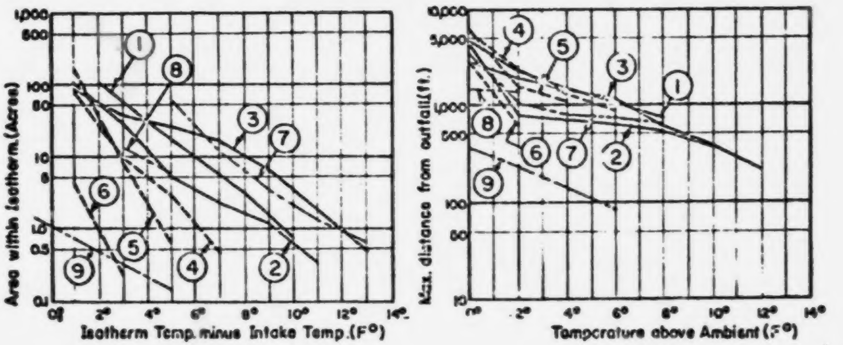


Figure 10-1. General pattern of infrared survey flight tracks (from Squire, 1538).



10-2a. SURFACE ISOTHERMS, Run No.2, Sept.12, 1963.

Run No.	1	2	3	4	5	6	7	8	9
Average MW	758	833	868	570	200	160	660	660	660



10-2b.

10-2c.

Figure 10-2. Off-shore temperatures.

MORRO BAY POWER PLANT
(from Cheney and Richards, 1507)

vicinity of the outfall indicate the warm water is normally confined to a layer approximately 10 feet thick. The degree of wind mixing dictates the extent to which these temperature gradients diminish. Comparison with surface temperatures showed that the airborne radiometer was accurate to ±1F° except under conditions of fog or smoke when the error could be as much as 3 or 4F°.

In 1968 North and Adams (1531) collected data from nine thermal power stations which included measurements of the surface areas enclosed by isotherms drawn from infrared measurements. From these data (35 measurements) a regression equation was calculated to determine the correlation between power output at a generating station and the surface area enclosed by contour lines 10F° and 2F° above ambient. The wide scatter in the data resulted in a rather poor correlation.

Maps produced from radiometric data require subjective interpretation of the data points to plot isotherms (Doyle and Gormly, 1509). An objective map can be produced if the area under consideration can be rapidly scanned and a computer program used to compose and draw the map. PG&E began using a thermal mapper in 1967 to conduct their airborne surveys. The thermal mapper is an airborne device, sensitive to infrared radiation, used to mechanically scan the scene in its field of view in a line by line fashion. The output can be recorded on film as an analogous image or on magnetic tape (Doyle and Cartwright, 1508). A computer program digitizes the analog data from the magnetic tape and constructs a map of surface isotherms (Figure 10-3). Additionally, the isotherms can be integrated by computer to yield a temperature-area relationship. This relationship is used to compare theoretical and prototype values from which projections of thermal influence from plant enlargements can be made (1509). Regression equations for each plant have been computed showing the area of influence as a function of excess temperature.

Since July 1963 an oceanographic monitoring program has been conducted by Marine Advisers, Inc. for the San Onofre nuclear generating station (Marine Advisers, 1153 and 1154). This power plant utilizes a 2,600 foot submerged outfall discharging 350,000 gal/min of coolant in approximately 25 feet of water. Sampling was conducted monthly using standard oceanographic equipment. Since 1969 occasional airborne infrared radiometer surveys have been made

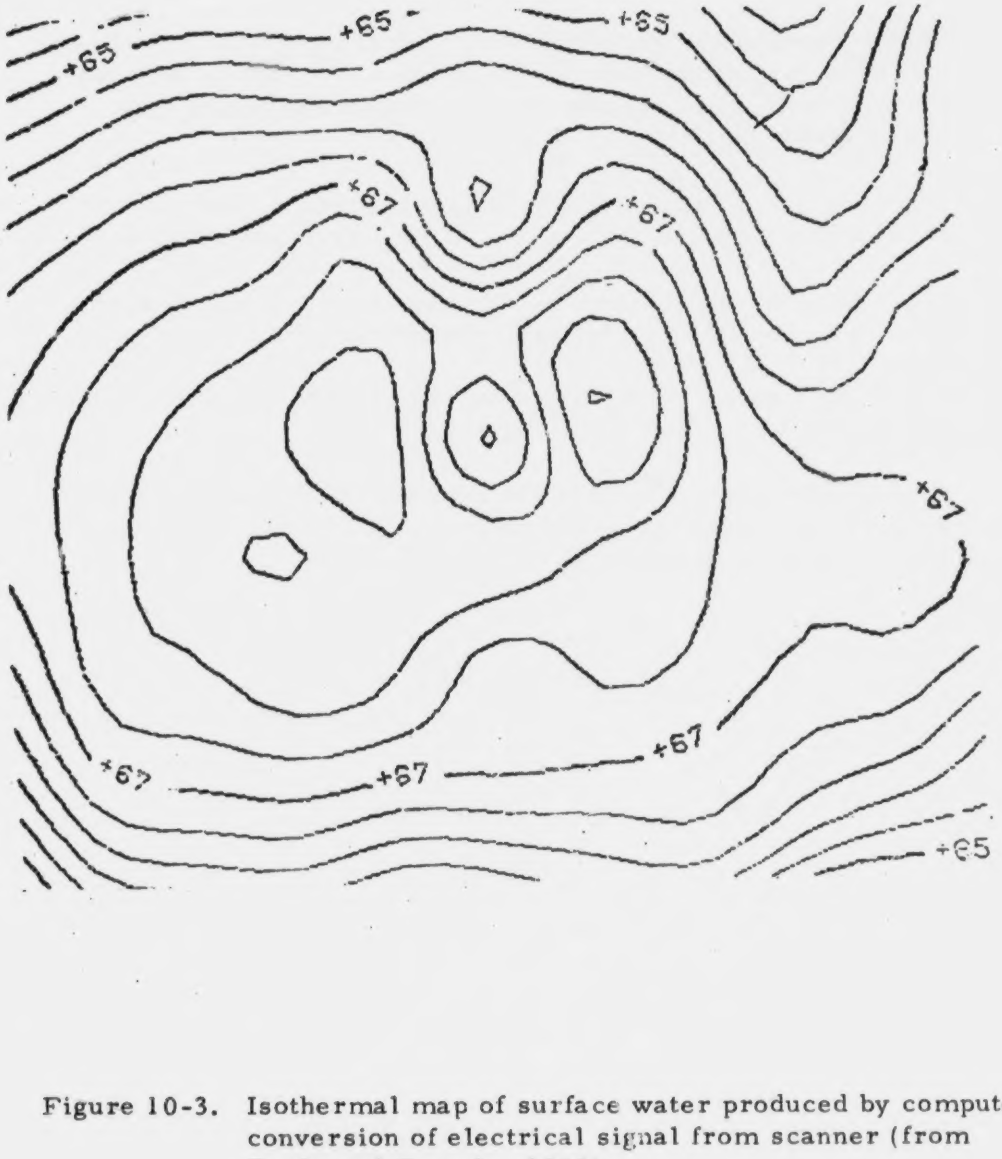


Figure 10-3. Isothermal map of surface water produced by computer conversion of electrical signal from scanner (from Doyle and Gormly, 1535).

to supplement the oceanographic surveys.

Conclusions reached during the 5-year monitoring period are (1154):

1. The largest temperature increase at the outfall boil was 9F°, but generally it is less than 6F° (normal temperature rise across the condenser is 18F°).

2. Surface areas containing waters warmed more than 4F° are confined to the immediate vicinity of the outfall boil (Figure 10-4).

3. The maximum distance from the outfall the warm water plume has been detected is 2 miles in the longshore direction.

4. The thermal plume was confined to a shallow surface lens, normally 5 to 12 feet thick (Figure 10-5).

5. From data available there seems to be little correlation between the area influenced by the warm water discharge and the local current speed and direction.

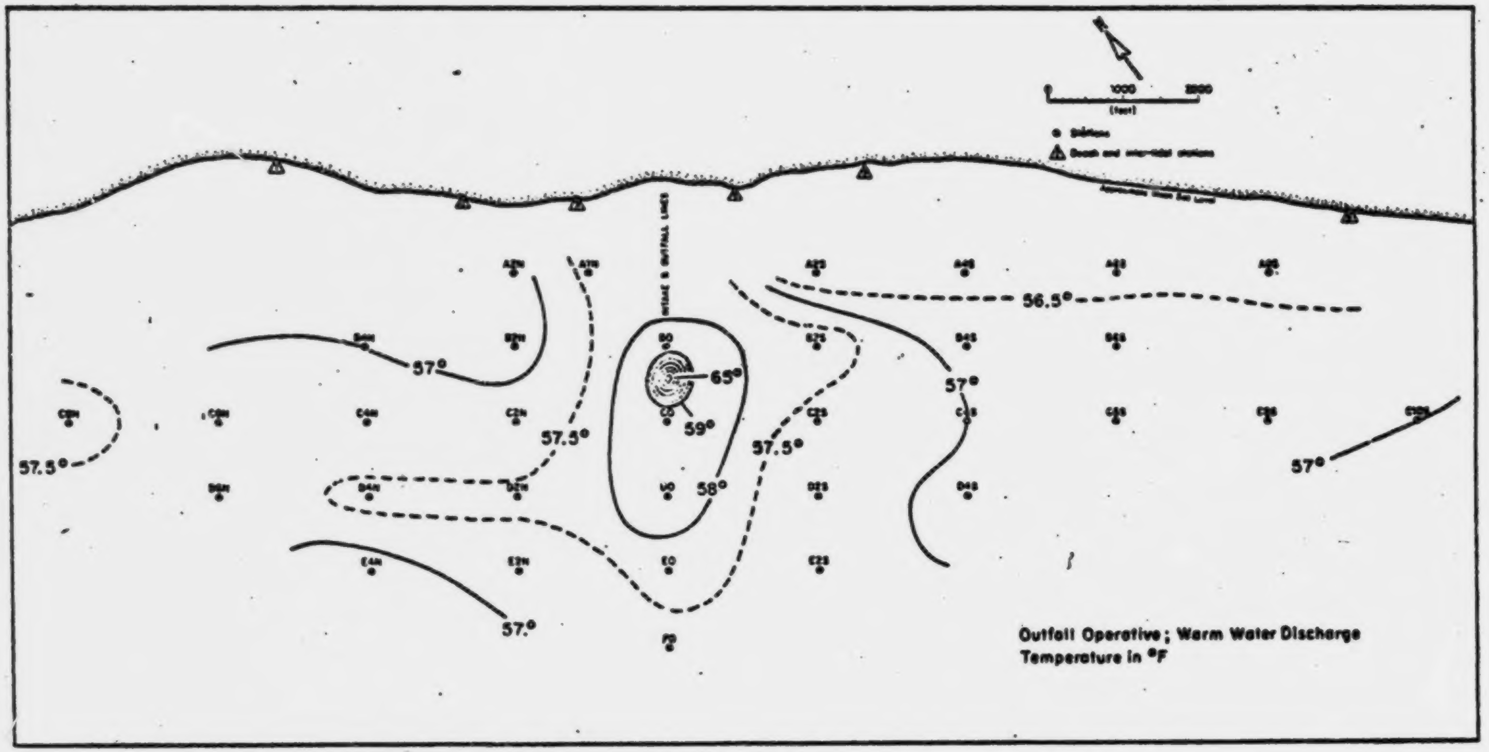


Figure 10-4. San Onofre sea surface isotherms, 21 February 1969 (from Marine Advisers, Inc., 1154).

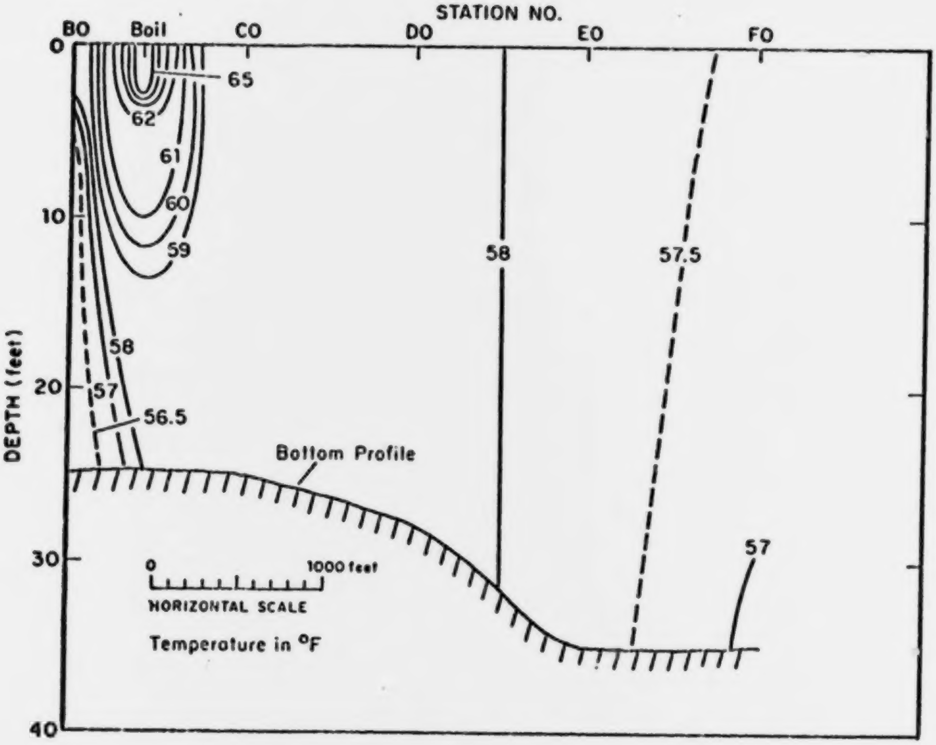


Figure 10-5. Temperature-depth cross sections, 21 February 1969 (from Marine Advisers, Inc., 1154).

Chapter 11. REVIEW OF ANALYTICAL MODELS FOR THE PREDICTION OF TEMPERATURE DISTRIBUTION

by Robert H. Bourke and Bard Glenne

Introduction

Analytical models to determine the distribution pattern of heated effluents discharged into ambient fluids are based on theory developed for the disposal of sewage effluent. This type effluent is usually discharged through multiport diffusers into the receiving water where it undergoes mixing and dilution from the action of essentially two distinct mechanisms: (1) turbulence and momentum associated with discharge jets, and (2) natural turbulence and currents within the receiving water body (Brooks, 1504).

Upon discharge from the end of an outfall pipe or diffuser port an effluent possesses kinetic energy due to its velocity. This energy is dissipated by the turbulent mixing of the jet with the surrounding fluid. This mixing process is commonly termed "jet mixing." During the jet mixing phase the turbulent jet entrains part of the surrounding fluid resulting in an increasing volume flux with increasing distance from the outlet while simultaneously decreasing the jet velocity.

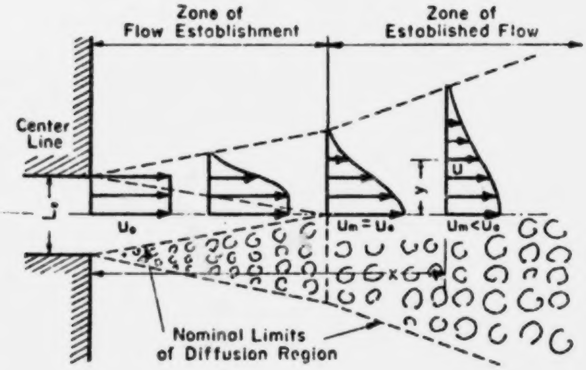


Figure 11-1. Schematic representation of jet mixing (from Wiegel, 1542).

The boundary between the jet and the receiving fluid is a region of instability where high shear stresses exist. Mixing will occur with a subsequent interchange of properties and constituents (Wiegel, 1542). In the zone of flow establishment (Figure 11-1) the centerline jet velocity, U_0, is considered constant with longitudinal distance. Within the zone of established flow mixing takes place throughout the jet. The velocity profile across this zone is assumed to be Gaussian. The investigations of Frankel and Cumming (1518) have shown that the concentration of effluent can also by reasonably assumed as Gaussian in the established flow zone.

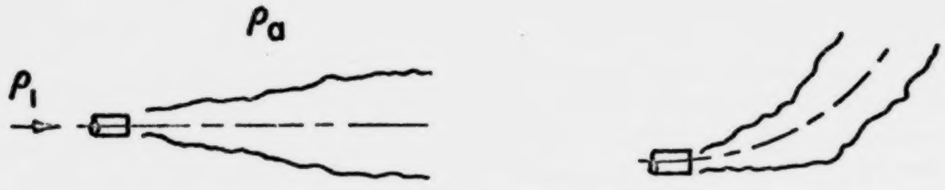
Within a short distance from the outlet the velocity of the jet will be dissipated. If the fluid in the jet has a different density than the receiving fluid, it will also possess potential energy. Mixing will occur as the potential energy is dissipated by the discharge rising or falling. The combination of this mixing and jet mixing is often termed "initial dilution." Further mixing may occur due to natural turbulence and currents within the water body and the wind over it (1504). When this mixing takes place on the ocean or a lake surface, it may be termed "surface dispersion and interface exchange." In this zone the effluent may move across the water surface in the form of a dispersive plume.

Environmental Effects

The disposal of waste heat from thermal electric generating plants discharging into the ocean, requires that certain environmental factors be taken into consideration. The major factors and their effects are discussed below:

(a) Buoyancy Effect

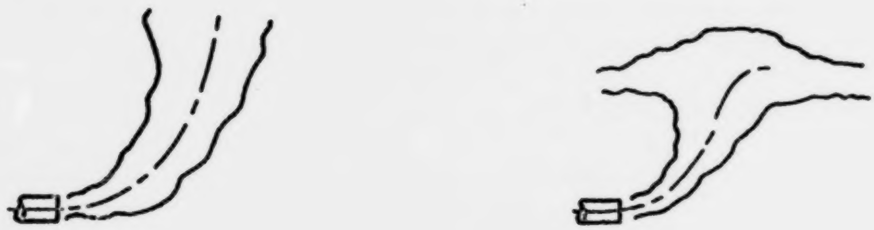
The density of the condenser discharge from a thermal-electric generating plant will usually be less than that of the surrounding sea water. This density difference, although quite small, creates a buoyant force which measurably affects the behavior of the jet (Figure 11-2). A jet which contains an initial buoyancy flux as well as momentum flux is termed a "buoyant" jet (Fan, 1515). The buoyancy force is proportional to the difference in density between the sea water and the rising jet and generally decreases as the jet ascends (1518).



No density difference $(\rho_1 = \rho_a)$

With density difference $(\rho_1 < \rho_a)$

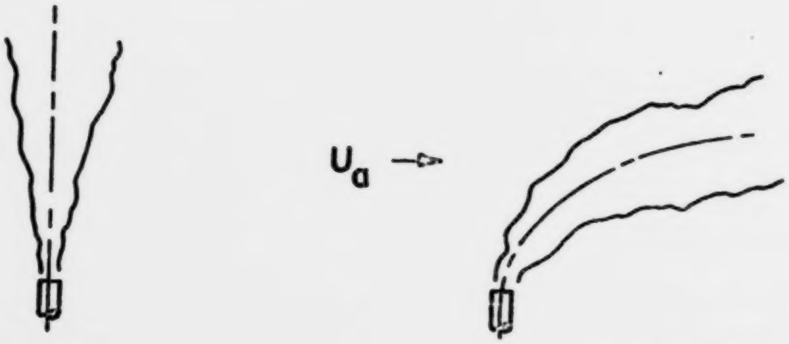
Buoyancy Effect



Homogeneous $(\rho_a = \text{constant})$

Stratified $(\rho_a \neq \text{constant})$

Stratification Effect



Stagnant $(U_a = 0)$

With current $(U_a \neq 0)$

Current Effect

Figure 11-2. Effects of environmental conditions (from Fan and Brooks, 1515).

(b) Recipient Density Stratification Effect

Vertical temperature and/or salinity gradients in the ocean cause density stratification of the water column. As the heated effluent rises through the water column, it mixes with the sea water and the mixture generally becomes more dense. If the density of the mixture becomes equal to that of the receiving fluid (which is usually less dense near the surface), the ascending motion ceases and the mixture tends to spread horizontally (Figure 11-2). It may be possible to obtain a plume which is completely submerged below a strong thermocline (Rawn, et al., 1535). The submergence of a sewage field is often a most favorable situation for coastal pollution control (1515). However, the heated discharge from steam electric generating plants will most likely rise directly to the surface due to the large density difference and flow rate.

(c) Ocean Currents Effect

The ocean currents may affect not only the dispersive plume established at or near the sea surface, but also the jet mixing characteristics (1515). The ocean currents usually consist of large scale ocean currents, tidal currents, wind drift currents, and currents due to waves. Although some of these currents may not produce a net transport of water, they are the causes of turbulence which mixes the waters in a process akin to diffusion.

(d) Atmospheric Effects

An important factor in the dissipation of heat from surface water is the condition of the atmosphere. Air temperature, winds, air humidity, and solar radiation all influence the sea-air heat transfer rate.

Analytical Models

Analytical models have been proposed by investigators to describe temporally and spatially the fate of constituents and pollutants when discharged into lakes, estuaries, and oceans. The following sections are a review and analysis of models pertinent to the discharge of thermal effluents into coastal waters.

The discharge of cooling water from thermal electric plants generally takes place via one of two methods: (1) from a submerged pipe at a significant depth and distance offshore, or (2) from a canal which discharges into the ocean at the shoreline. Research has indicated that for both types of discharges cooling of heated effluent may occur via two processes: (a) initial dilution upon emission from the outlet pipe or canal, followed by, (b) surface dispersion and sea-air interface exchange.

Part I. Initial Dilution

(a) Submerged Jets

The turbulent mixing process that occurs when one fluid is discharged into another is a problem for which the theory is relatively well known. The reference lists of Fan and Brooks (1515) and Cederwall (1505) contain papers which have contributed to the understanding of turbulent jet phenomenon. Cederwall (1505) presents a detailed review of these studies as related to marine waste water disposal. Sewage outfalls are now often designed after the procedures developed by Rawn, Bowerman, and Brooks (1535) and Brooks (1504).

Frankel and Cumming (1518) advanced the initial studies of Rawn, et al. and Brooks by investigating the efficiency of various discharge angles of pipes. They found the horizontal diffuser to give the least concentrations, but that differences in concentration levels for various discharge angles became insignificant for a ratio of diffuser depth to diffuser diameter greater than 50.

Theory seems to underpredict concentrations in the surface transition zone where vertical flow changes to lateral spreading, Figure 11-3, (1535).

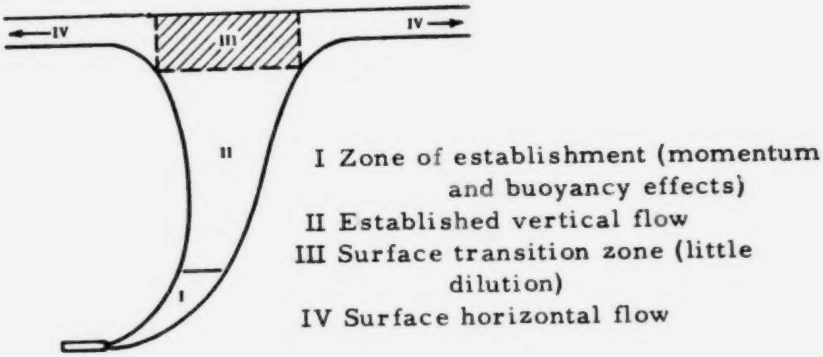

IV
III
IV
II
I
I Zone of establishment (momentum and buoyancy effects)
II Established vertical flow
III Surface transition zone (little dilution)
IV Surface horizontal flow

Figure 11-3. Zone configurations of a jet for the case of a stagnant, homogeneous environment. (from Frankel and Cumming, 1518).

Fan (1514) showed that for a vertical jet, the trajectory of the plume was bent toward the downstream direction of flow (Figure 11-2). Turbulence induced by currents within the receiving fluid may also affect the initial dilution, but these effects generally are minor.

(b) Stability Considerations

A measure of the stability of a water column is provided by the Richardson number, Ri, which indicates the degree of turbulence present. The Richardson number may be expressed as:

$$Ri = \frac{g}{\rho} \frac{\partial \rho}{\partial z} \Big/ \left(\frac{\partial u}{\partial z}\right)^2 \qquad 11\text{-}1$$

where the numerator and denominator, respectively, describe the strengths of the vertical gradients of density and velocity within the water column.

A large density gradient or small vertical velocity gradient results in a large value of Ri which indicates supression or extinction of turbulence. A small Ri generally indicates maintenance or an increase of turbulence.

Near the discharge orifice the Ri of the jet is quite small due to the large vertical shear; the turbulent and momentum fluxes are at a maximum. With increasing distance from the orifice the turbulent and momentum fluxes decrease increasing the Richardson number. The Richardson number, therefore, measured as a function of the distance from the discharge point, indicates how rapidly the momentum of the jet decays. As discussed previously, the amount of ambient cooling water entrained by the jet decreases as the velocity decreases; hence, further cooling of heated jets by turbulent mixing becomes insignificant for large Ri.

The experiments of Hayashi and Shuto (1521) confirmed that for small Richardson numbers (less than one) turbulent mixing was the most influential factor in reducing the temperature of the jet.

In practice the Richardson number is difficult to determine. Generally, velocity data is not available to determine vertical velocity gradients in the vicinity of the plume. The densimetric Froude number, N_F, is often used instead.

$$N_F = U_o \Big/ \sqrt{(\Delta\rho/\rho_o)\, g\, D_o} \qquad 11\text{-}2$$

where U_o is the initial discharge velocity of the jet,

$\Delta\rho/\rho_o$ is the relative initial density difference between condenser discharge and ambient water,

D_o is either initial discharge depth or outfall diameter.

Experimentation has shown that the relative density difference is the most significant factor in determining the type of pollutant field that may develop (Wiegel, 1542). Weak or negative relative density gradients result in a surface field; strong relative gradients in a submerged field. The relatively large negative density difference and large volume flow rate associated with thermal power plant discharges usually dictate that the heated effluent will spread as a surface field.

(c) Horizontal Surface Jets

Commonly, thermal power plants discharge their cooling water through a channel or canal into the ocean at the edge of a beach. The work of Abraham (1500) indicates a relationship for the distribution of salinity in a horizontal surface jet. When slightly modified, this relationship can be used for the distribution of temperature in the jet if the buoyant effect of the warm water is small. Such a relationship takes the form (Jen, et al., 1524):

$$T^* = \frac{T - T_w}{T_o - T_w} = \frac{1}{2C_1}\,\frac{D_o}{x}\exp\left[-\frac{1}{2C_1^{\,2}}\,\frac{r^2}{x^2}\right] \qquad 11\text{-}3$$

where T^* is a dimensionless surface temperature i.e. the "temperature concentration,"

T_w is the temperature of the receiving water (°F),

T_o is the temperature of the jet prior to mixing (°F),

D_o is the diameter of the jet (ft),

x is the horizontal distance along the jet axis, measured from the point of discharge (ft),

r is the radial distance normal to the jet axis (ft),

C_1 is an experimentally determined dimensionless constant, ≈ 0.096.

Equation 11-3 is characteristic of jets with densimetric Froude numbers which are large when compared to unity (Harleman and Stolzenbach, 1520). High discharge densimetric Froude numbers indicate entrainment of the underlying cool water; rapid thickening of the jet takes place until the Froude number decreases to below unity (Lean and Whillock, 1527).

For buoyant discharges having smaller densimetric Froude numbers, but greater than unity, Jen, et al. (1524) found that the buoyancy does not appreciably affect the entrainment dilution. However, the buoyancy tends to distort the temperature distribution from that of the non-buoyant jet by horizontally expanding the plume. For this condition Jen, et al. found the best temperature description to be:

$$T^* = \frac{1}{2C_1}\,\frac{D_o}{x}\,\exp[-C_2(N_F)^{1/2}(y/x)^2] \qquad 11\text{-}4$$

where C_2 is an experimentally determined dimensionless constant,

N_F is the densimetric Froude number, and

y is the horizontal distance normal to the jet axis, measured from the axis of the jet (ft).

For dimensionless distances (x/D_o) between 7 and 100 and densimetric Froude numbers ranging from 18 to 180, equation 11-4 can be expressed as:

$$T^* = 7.0\,\frac{D_o}{x}\,\exp[-3(N_F)^{1/2}(y/x)^2] \qquad 11\text{-}5$$

An important result indicated by equation 11-4 is that along the centerline of the jet the discharge temperature decreases as 1/x.

In a continuation of the above study Wiegel, Mobarek, and Jen (1541) investigated the mixing efficiency of horizontal surface jets discharging over sloping bottoms. The constants C_1 and C_2 in equation 11-4 were found to be dependent on the bottom slope and also on the ratio of height to width of the rectangular nozzels used to represent the discharge channel or canal. Wiegel, et al. concluded that steeper slopes resulted in more thorough mixing and, hence, a more rapid cooling of the effluent plume. Beaches with shallow sloping profiles do not provide enough water for optimum entrainment. The mixing capability at "low, mid, and high tide" conditions were examined. The greatest amount of mixing occurred logically at high tide.

Wiegel, et al. also observed that jet mixing depends upon the jet discharge velocity. Low velocities result in laminar or low level turbulent mixing, while high velocities produce "high level" turbulent mixing with large scale eddies at the jet boundary entrapping the surrounding receiving water.

Part II. Surface Dispersion and Interface Exchange

(a) Surface Dispersion

Hayashi and Shuto (1521) investigated heated jets including the case of no entrainment, i.e., the velocity of the jet decreased to nearly zero. For this condition they found the Richardson number to have increased to a value slightly greater than one. This is the regime of "horizontal or surface dispersion and interface exchange."

In this regime the plume of hot waste is mixed and transported away from the region of the source by the action of surface currents. The depth of the plume slowly thickens with distance from the source due to surface mixing. Heat may also be emitted to the atmosphere.

The equation developed by Hayashi and Shuto to predict surface temperatures within the dispersive plume (condition of negligible entrainment) is:

$$T^* = \exp[\ -C_3 \frac{K}{\rho c_p} \frac{B_o^2}{Q_o} \{ 1 + \left(\frac{y}{x}\right)^2 \}^2 \left(\frac{x}{B_o}\right)^2] \qquad 11\text{-}6$$

where K is an atmospheric heat exchange coefficient (Btu $\cdot F^{-1}$ ft^{-2} sec^{-1}),

B_o is the width of the outlet (ft),

Q_o is the flow rate (cfs),

C_3 is an experimentally determined dimensionless constant.

This relationship has been corroborated by the work of Harleman and Stolzenbach (1520) using a hydraulic model. Equation 11-6 indicates a temperature reduction at the rate e^{-Cx^2} where C is a function of the outlet width, B_o, and discharge flow rate, Q_o. Harleman and Stolzenbach's experiments with surface discharges showed that the centerline temperature decreased as $1/x$ until a distance of $x/B_o \approx 30$ was reached when the decrease became more rapid and was well represented by $T^* \sim e^{-Cx^2}$.

From their hydraulic model study Harleman and Stolzenbach concluded that changes in tidal elevation, condenser flow rate and current velocities do not significantly affect temperature distribution, but actual field studies have shown that these factors can affect temperature distributions.

(b) Interface Exchange

Heat exchange with the atmosphere must be considered once the turbulent motion of the jet has decreased to a level where entrainment of the surrounding cooling water is low. Equations which include this phenomenon are essentially similar to those used to predict the dispersion of sewage, pulp mill wastes, or radionuclides except that the non-conservative term (decay term) now must account for the air-sea interface heat exchange.

The net rate of heat exchange across the air-sea interface, ΔH, can be expressed as the algebraic sum of: H_b, the effective long wave back radiation; H_e, the evaporative heat flux; and H_c, the sensible heat flux.

To overcome the difficulties inherent in directly measuring the net heat flux from its component terms, Edinger and Geyer (1512) have approximated the net rate of heat exchange across the air-sea boundary by:

$$\Delta H = K (T_w - T_e) \text{ Btu Ft}^{-2} \text{ Day}^{-1} \qquad 11\text{-}7$$

where K is the surface heat exchange coefficient (B Ft^{-2} Day^{-1} $°F^{-1}$),

T_w is the actual water temperature (°F),

T_e is the equilibrium temperature (°F).

Edinger and Geyer define the equilibrium temperature, T_e, as the water temperature at which there is no net heat exchange across the water surface, i.e. $\Delta H = 0$. Procedures for the calculation of K and T_e are fully described by Edinger and Geyer (1512).

The dispersion of heated discharges into the ocean requires a model equation in at least two dimensional form. Following the development of Brooks (1504) for the dispersion and die-away of coliforms from a sewage outfall, Edinger and Polk (1510) derived a model to predict the temperature distribution based upon the lateral dispersion of heat into a uniform longitudinal velocity field with no vertical temperature gradient. Although the authors developed this model primarily for rivers and lakes, they applied it to a coastal zone environment (Morro Bay, California) with some success. The steady state non-conservative distribution may be expressed as:

$$u\frac{\partial\theta}{\partial x} = \frac{\partial}{\partial y}\left[D_y\frac{\partial\theta}{\partial y}\right] - \frac{K\theta}{\rho c_p d} \qquad 11\text{-}8$$

where the three terms represent the rates of decrease of excess temperature per unit volume for longitudinal advection, lateral diffusion, and atmospheric cooling. Edinger and Polk choose a solution for a constant D_y (ft^2/day) which results in a conservative decay of temperature:

$$\frac{\theta(\xi,\ y)}{\theta_p} = \left(\frac{\xi_s}{\xi}\right)^{1/2} e^{-\frac{y^2}{4\xi}}\ e^{-\alpha(\xi-\xi_s)} \qquad 11\text{-}9$$

where $\theta(\xi, y)$ is the temperature rise (°F) at some specified lateral coordinate, y, and longitudinal coordinate, $\xi = \frac{xD_y}{u}$, where u is a constant stream velocity (ft/sec),

θ_p is the temperature rise across the condenser (°F),

ξ is the position of the source given by $\xi_s = \frac{1}{\pi}\ \frac{Q_p{}^2}{ud}$

where Q_p is the flow rate through the condenser (cfs) and d is the depth of the water (ft), and

α is a coefficient governing the rate of heat loss at the surface,

$$\alpha = \frac{K}{\rho c_p D_y d}$$

where K is the surface heat exchange coefficient (Btu °F^{-1} Day^{-1} Ft $^{-2}$).

The reduction in temperature of the outfall plume may more conveniently be expressed as the surface area contained within given temperature rise contours. Figure 11-4 from Edinger and Polk shows the relationship of the temperature rise ratio, θ_c / θ_p, to the non-dimensional surface area ratio, A / A_n, for selected values of β, a dimensionless coefficient governing the rate of heat decay at the surface. For selected values of β, Edinger and Polk found that atmospheric cooling had little influence on temperature

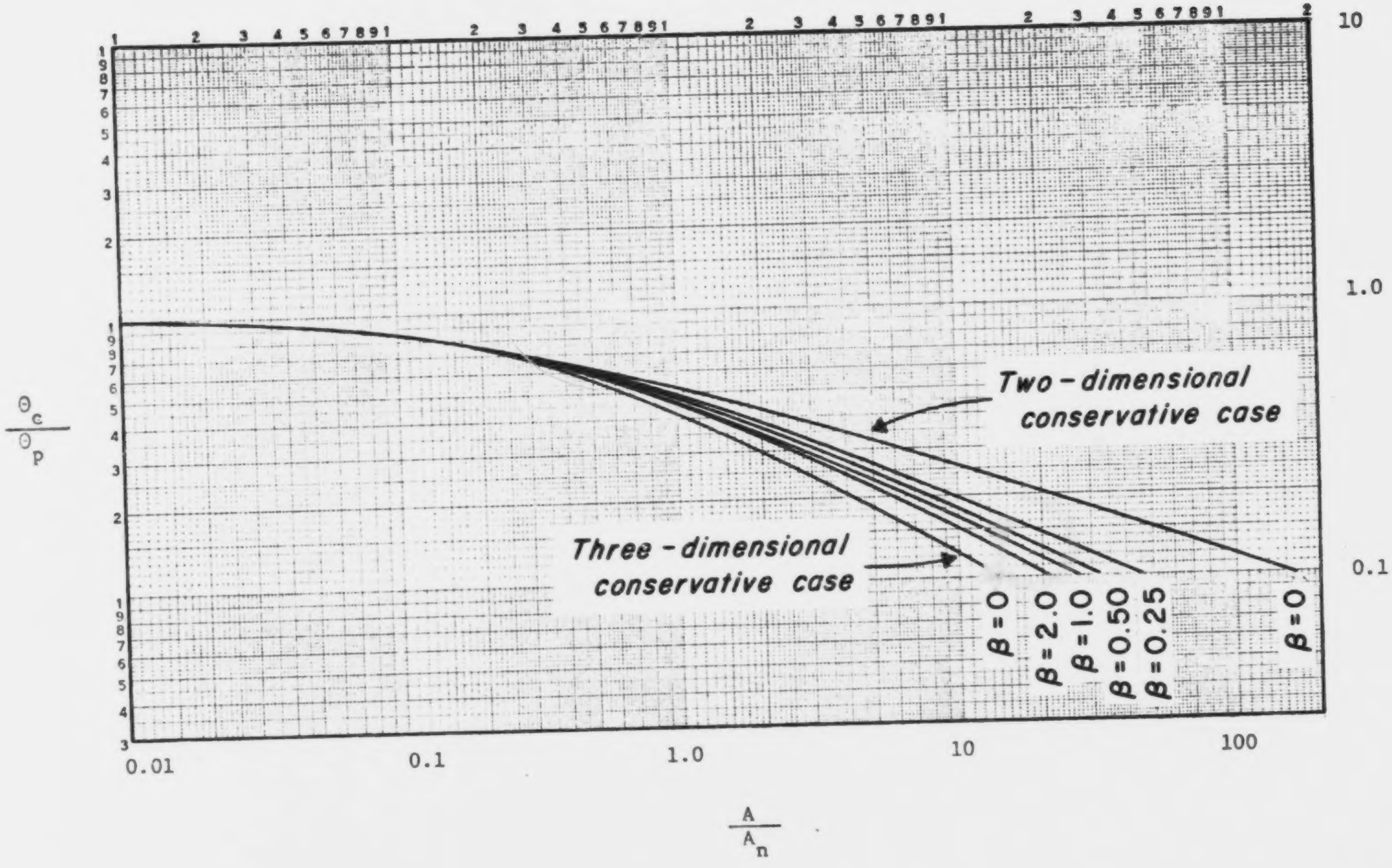


Figure 11-4. Relationship of temperature rise ratio to non-dimensional surface area ratio for selected values of β, a dimensionless coefficient governing the rate of heat decay at the surface (from Edinger and Polk, 1510).

reduction until θ_c/θ_p had decreased to 0.60. For values of θ_c/θ_p greater than 0.60 turbulent mixing was the dominant process in reducing the plume temperature. These conclusions are similar to those postulated by Hayashi and Shuto (1521) and corroborated by Harleman and Stolzenbach (1520).

Edinger and Polk also investigated a three dimensional conservative model (no heat exchange across the air-sea boundary) which included a vertical mixing term. For this case temperatures were reduced at a faster rate than for the two dimensional non-conservative case (Figure 11-4).

(c) Hydraulic Models

Concerning the model laws for coastal and estuarine hydraulic models Keulegan (in 1144, p691) states:

> "Many of the flow conditions encountered in the natural phenomena around coasts and estuaries unfortunately are not amenable to mathematical analysis. The difficulty may be due to the nonlinear character of the equation of motion, to a lack of information on existing turbulence and effective diffusion coefficients in instances of mixing, to the multiplicity of interconnected flow passages....In such cases it becomes necessary to resort to models in order to predict the behavior of a prototype and in some instances to observe, in the model, details that are not readily examined in nature."

Hydraulic models should not be treated as a substitute for field and analytical studies, but should be considered as an aid to such studies by contributing information not accurately obtained by other means.

Most hydraulic models are distorted geometrically in that the vertical scale is exaggerated with respect to the horizontal scale. Such distortion is a consequence of the need to have workable water depths and non-laminar flow in the model. The degree of distortion is dependent on the area to be reproduced and the nature of the problem to be investigated. In order to reproduce frictional effects the model may be "roughened" (generally vertically mounted thin metal strips are used).

In general, satisfactory model verification can be achieved for kinematic quantities (i.e., velocity, height, etc.); however, to simulate water quality parameters (i.e., salinity, temperature, etc.) is much more difficult. Vertical exaggeration prevents accurate simulation of beach slope, channel geometry (depth to width ratios) and lateral dispersion by turbulence (Ackers, 1503). In the vicinity of the jet where turbulent entrainment is dominant geometric similarity is also necessary.

To circumvent these incompatibilities two models may be used: (1) an undistorted scale model of the area near the outfall to represent initial dispersion and the buoyant plume zone, and (2) a vertically exaggerated model to represent the whole area of interest (1503). Another method is to build a distorted model and attempt to interpret the affects of differences of the non-similar parameters on the temperature distribution (1520).

Modeling of power plant outfalls has been practiced extensively in Great Britain, Japan and the United States. In Great Britain the Hydraulics Research Station at Wallingford and the University of Strathclyde at Glasgow are the principal institutions engaged in hydraulic model research. The reference lists of Ackers (1503) and Frazer, et al. (1551) list pertinent papers in this field. In the United States hydraulic modeling centers are the U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.; the U. S. Army Corps of Engineers' San Francisco Bay-Delta model; the Coastal Engineering Research Center, Washington D. C.; Massachuetts Institute of Technology; and the University of California, Berkeley.

(d) Numerical-Hydrodynamic Models

Solutions to most of the analytical models discussed in the previous sections are possible only when simplifying assumptions are made, e. g., boundaries are of regular shape, distribution of velocity is simple, etc. Such simplifications may result in solutions which sometimes have little connection with actual conditions.

With the advent of high speed computers it has become possible to solve model equations using numerical methods (i. e., using a finite difference scheme) which eliminates the need for some of the simplifications. Applications of numerical hydrodynamic (N-H) models were initially developed for rivers and estuaries (Callaway, et al., 1545; Bella and Dobbins, 1550; Fisher, 1547; Glenne, 1548; Kent, 1549). Recently several N-H models have been devised for application to open coasts. Among these are the Walter Hansen model used by the Fleet Numerical Weather Central (Laevastu and Stevens, 1526) and the Leendertse model (1529).

Obtaining a solution to an N-H model may be quite costly. Laevastu and Stevens comment that the model must be run ten to sixty hours in real time (dependent on the size of the area and grid length) before a correct solution is obtained. This long running time is that required for initial convergence, but after a converged solution is obtained, it may be that it can be inserted repeatedly into a program which solves the advection-diffusion equation.

Part III. Dye Diffusion Studies

The use of dyes to study the movement and dispersion characteristics of effluent plumes has become widespread with the advent of sensitive measuring devices (Pritchard and Carter, 1534; Yudelson, 1543; James and Burgess, 1523; Ichiye, 1522; Foxworthy, 1516). The vast majority of these studies have been oriented towards the disposal of sewage. The use of dyes to trace the distribution of heated effluents, however, has been limited since the distributions obtained from tracer experiments have to be corrected for the cooling process at the air-sea boundary.

Pritchard and Carter (1534) have proposed a technique to account for the non-conservative process of heat loss at the surface when rhodamine dye is used to trace the effluent plume. The rhodamine dye must be injected into the water body in a special manner to take into account the large differences in volume rates of flow of dye and effluent. The concentration of dye is then related to the concentration of heat through an expression which takes into account the flow rates and mixing depths of both dye and effluent, i.e.

$$\Gamma_{h,\infty} = \frac{Q_h}{Q_d} \cdot \frac{D_d}{D_h} \int_0^\infty \frac{\partial}{\partial t} \left[\Gamma_d(t)\right] e^{-\gamma t/D_h} \, dt \qquad 11\text{-}10$$

where $\Gamma_{h,\infty}$ is the steady state concentration of heat in Btu lb^{-1},

$\Gamma_d(t)$ is the concentration of dye at time t in ppb (10^{-9} lb/lb),

Q_h and Q_d are the flow rates of heated effluent and dye, in Btu day^{-1} and lb day^{-1}, respectively,

D_d and D_h are the mixing depths of the dye and heated effluent, respectively, in feet, and

γ is a rate coefficient which represents the loss of excess heat to the atmosphere which for summer conditions was found to be approximately 0.1 ft hr^{-1}.

The time dependent concentration of dye, $\Gamma_d(t)$, was found to approach the steady state value, $\Gamma_{d,\infty}$, asymptotically at a constant rate, η , which by best fit of the data was approximately 1.0 day^{-1}. After making appropriate substitutions integration of equation 11-10 yielded the steady state concentration of heat as functions of the steady state dye concentration emitted from a continuous source and of the flow rates and mixing depths of dye and effluent:

$$\Gamma_{h,\infty} = \frac{Q_h}{Q_d} \cdot \frac{D_d}{D_h + \gamma/\eta} \cdot \Gamma_{d,\infty} \qquad 11\text{-}11$$

PART II - CHEMICAL AND RADIOCHEMICAL ASPECTS

We wish to know the chemical characteristics of the nearshore waters of the Pacific Northwest in order to make reasonable assessments of the possible effects of the addition of industrial effluents. Dissolved oxygen, inorganic micronutrients, pH, CO_2 tension, trace metals, radionuclides, pesticides, and pulp mill effluents have been considered. Although this list does not include all constituents which might have been studied, it does attempt to cover the major ones.

The general rationale for considering these factors can be simply stated: that factors in the environment favorable to an organism tend to reduce the effect of a harmful substance, and that factors unfavorable to the organism tend to increase the effect. The various factors can be interacting or independent. If interacting, they can be "synergistic" or antagonistic. Although theories relating to the toxicity of complex effluents in sea water are very crude, they do outline the necessity of characterization of those substances which affect how the system reacts to a specific effluent.

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Chapter 12. CARBON DIOXIDE AND pH

by Stephen W. Hager and Robert H. Bourke

Studies of the nearshore concentrations of dissolved CO_2 in the Pacific Northwest have been only recently undertaken. Only a few of the pertinent features will be presented.

1. The concentration of dissolved CO_2 in sea water in equilibrium with the atmosphere in nearshore areas is about 320 ppm (Park et al., 6093)

2. The concentration of dissolved CO_2 at a depth of 2.5m in the Columbia River in December 1968 ranged from about 600 to 1000 ppm (Park et al., 6093)

3. Sea water values in nearshore areas were as high as 525 ppm (Gordon and Park, 6092)

4. Sea water values in nearshore areas were as low as 155 ppm (Gordon and Park, 6092)

5. Observed pH values correlate very well with CO_2 values, according to the equation:

$$P_{CO_2} = \frac{[H^+]^2 \Sigma [CO_2]}{\alpha([H^+]^2 + [H]K'_1 + K'_1 K'_2)}$$

where P_{CO_2} is the partial pressure of CO_2 in air in equilibrium with the water, α is the solubility coefficient of CO_2 in sea water, $[H^+]$ is the hydrogen ion activity as measured with a pH meter, $\Sigma [CO_2]$ is the total CO_2 in the water, and K'_1 and K'_2 are the first and second apparent dissociation constants for carbonic acid (Gordon, 6288).

High CO_2 values are caused primarily by upwelling or by turbulent mixing across the thermocline. Land runoff may play a role in some areas. Low CO_2 values are caused by uptake of CO_2 by photosynthetic organisms.

Conclusions:

There are wide fluctuations in dissolved CO_2 concentrations (or P_{CO_2}) in nearshore areas. Due to the correlation between pH and P_{CO_2}, measurement of pH, $\Sigma[CO_2]$, and temperature is often adequate for determination of CO_2 concentrations (Park et al, 6093) Certain kinds of pollution such as surface active agents or organics may change this relationship.

Chapter 13. OXYGEN AND NUTRIENTS

by Stephen W. Hager and Robert H. Bourke

Dissolved oxygen, inorganic micronutrient (phosphate, nitrate, silicate) and pH data were obtained from NODC (see Appendix 6 for details), Oregon State University data reports (1231) and the California Water Quality Control Board (7014). The data were divided geographically into the sections shown in Figure 13-1. Only values from inside of 10 nautical miles were considered.

Monthly means for 0, 10, 20, 30 and 50 meters (where available) were obtained for each section and graphed against month. Values from 10 and 30m were not included on the graphs since presentation of surface, 20 and 50 meter values appeared to adequately describe the distribution of the parameters. The data for Section 3 are shown in Figure 13-2. Data from other sections are given in Appendix 6.

Generalized Features:

The data shown suggest that the water column from the surface to 20 meters is approximately homogeneous from October to April. During the upwelling season, approximately May to September, the waters at 20m appear to be much more strongly affected by the upwelled waters than do the surface waters. This can probably be attributed to more turbulent mixing in the surface waters.

There are no apparent latitudinal variations within our area.

Oxygen: These observations can be made concerning the data:

1. Average surface values are higher than 20m values throughout the year.

2. The highest and lowest surface O_2 values are found in the summer months, June, July and August. This is probably due to the competing influences of photosynthetic production and upwelling.

3. The averaged gradient between the surface and 20m is steeper in the summer months. Surface values are not lowered as much by upwelling as 20m values.

4. Surface O_2 values are about 6.3 to 7.0 ml/l (N. T. P.) unless affected by strong upwelling.

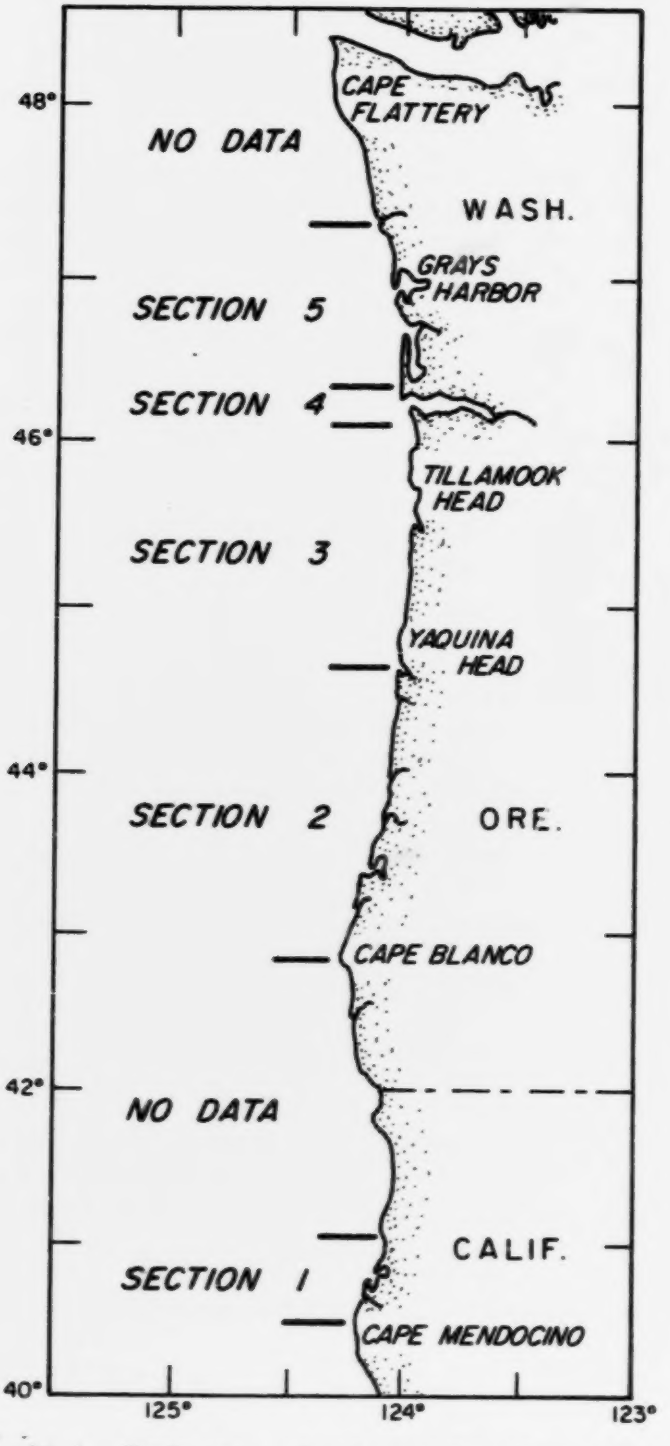

Figure 13-1. Study area, showing sections from which dissolved oxygen, nutrient, and pH data were taken.

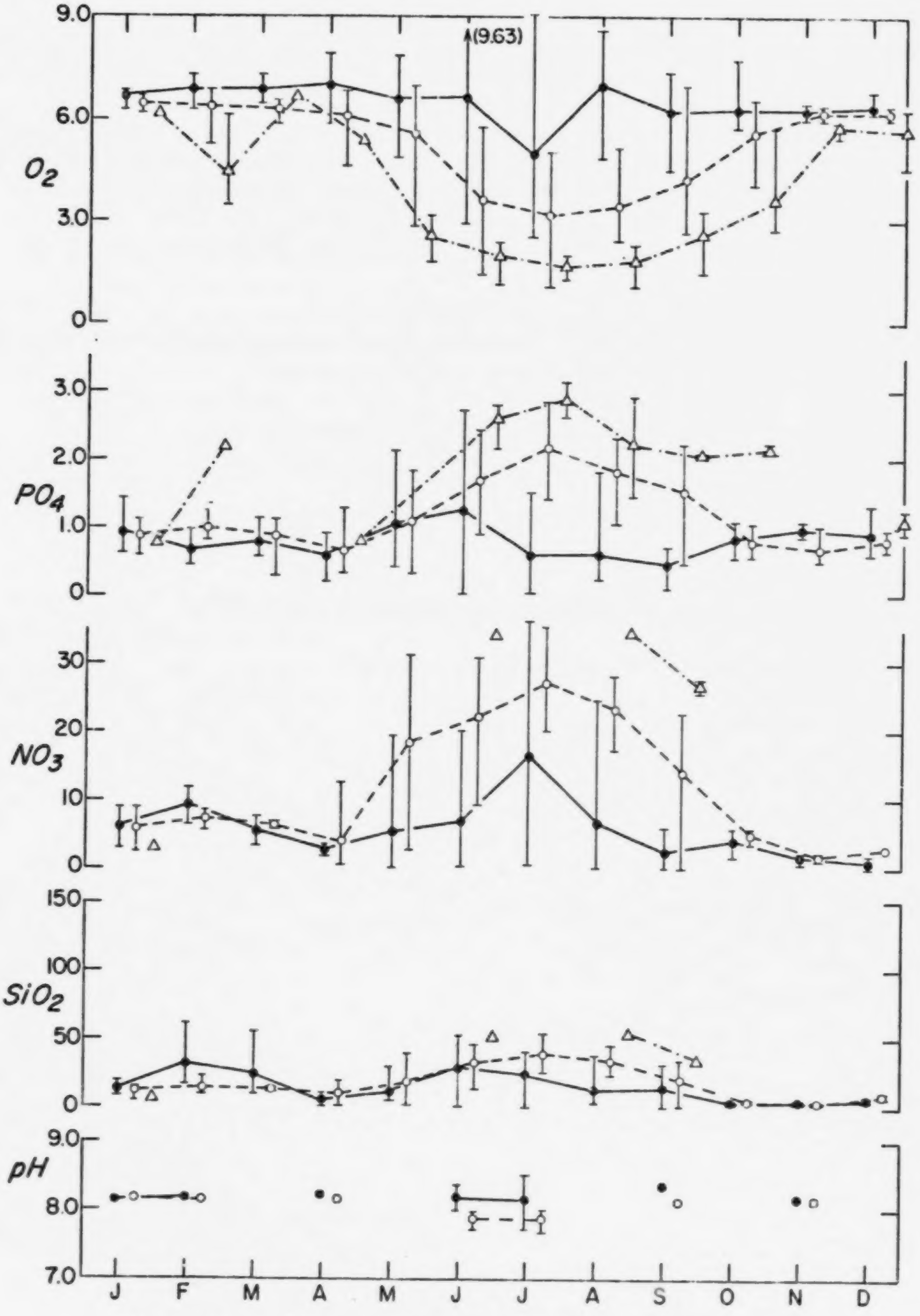

Figure 13-2. Data for Section 3, Newport, Oregon, to the Columbia River. Oxygen is in ml/l (N. T. P.). Nutrients are in μg-at/l.

Nutrients: These observations can be made concerning the three nutrients, phosphate, nitrate, and silicate:

1. The highest and lowest surface nutrient values are found in the summer months. Silicate values strongly affected by runoff may be higher at other times of year. Primary production and upwelling are probable causes of the wide variations in surface values.

2. The averaged gradient between surface and 20m is steeper in the summer months.

3. Exclusive of upwelling, representative surface nutrient values are:

   PO_4: 0.7 µg-at/l
   NO_3: 5 µg-at/l
   SiO_2: 10 µg-at/l

pH: Very few pH data were available. These tentative descriptions can be made:

1. pH values are lower in waters affected by upwelling.

2. Surface values are generally around 8.1.

Chapter 14. PULP AND PAPER INDUSTRY WASTES

by Stephen W. Hager

The Pacific Northwest supports a major pulp and paper industry. With increased restrictions on the introduction of wastes to river and lake waters, coastal waters may be increasingly used for disposal of the wastes from the industry. There are presently four pulp mills in our area with marine outfalls. Details of the locations and sizes of these operations are shown in Table 14-1 (Anon., 6319).

Three kinds of pulping processes are in general use: the kraft process, the sulfite process, and the groundwood process. In addition, associated bleaching or paper-making processes add to the mill wastes.

Wastes from pulp and paper mills are basically of two classes: solid wastes such as wood chips, bark, finely divided wood fibers, etc., and dissolved wastes which vary depending on the processes used.

The effects of pulp and paper industry wastes on the environment can be classified as either chronic or acute. Chronic effects generally involve changes in the sediments underlying the waters to which the wastes are discharged. The solid portion of the wastes contributes heavily to this "habitat destruction," although the role of dissolved materials sorbing on existing bottom sediments cannot be discounted (Howard and Walden, 6309). Acute effects include toxicity to organisms in the area, and avoidance reactions in organisms which would ordinarily migrate through the area (cf. Jones et al., 6310).

Kraft process:

The kraft process of wood pulping involves digestion of certain types of wood in a strong caustic solution containing sodium hydroxide, sodium sulfate, and sodium sulfide. The used solution is called the black liquor, and for economic reasons, 85-95% is recycled (Waldichuk, 6316). The wastes from a kraft pulp mill are mostly made up of the waters used to wash the pulp after it is physically separated from the black liquor.

The characteristics of kraft mill effluents are shown in Table 14-2.

Table 14-1. Pulp and paper mills in our area with marine outfalls.

1. Samoa, California. Georgia Pacific Corp.
   Kraft pulp mill. 550 tons bleached kraft market pulp per 24 hours.

2. Arcata, California. Crown-Simpson Pulp Co.
   Kraft pulp mill. 500 tons unbleached kraft market pulp per 24 hours.

3. Gardiner, Oregon. International Paper Company.
   Kraft pulp mill. 570 tons kraft containerboard per 24 hours, 545 tons unbleached kraft pulp per 24 hours

4. Toledo, Oregon. Georgia Pacific Corporation.
   Kraft paper and linerboard mill. 880 tons per 24 hours.
   Kraft pulp mill, 1075 tons unbleached kraft pulp per 24 hours.

Table 14-2. Kraft pulp mill effluents.

	kraft pulp process[1]	bleached kraft pulp process[2]
volume	20,000-30,000 gal/ton of product/day	35×10^6 gal/day
BOD	130 ppm	72 ppm
pH	7.5-9.0	3.4
total solids	1100 ppm	------

---

[1] California State Water Pollution Control Board, Publ. No. 17, generalized parameters (6300).

[2] Howard and Walden, for a specific mill (6309).

Note the significant pH difference between the effluents of mills producing bleached kraft pulp and unbleached kraft pulp.

The black liquor contains mercaptans, dimethyl sulfide, turpentine, methyl alcohol, ammonia, lignin, fatty and resinous acids, formic acid, acetic acid, lactonic acid, and sodium salts of organic and inorganic acids (McKee and Wolf, 6000). There may be other minor components which are important (Servizi, Gordon, and Martens, 6313).

The toxicity of kraft mill effluents to marine species has not been well studied. The results of studies reported in the literature are shown in Table 14-3. Other studies using diluted black liquor and synthesized draft mill effluent gave somwhat similar although less interpretable results (McKee and Wolf, 6000; Anon., 6299).

Attempts have been made to study the toxicity of individual components of the effluent (McKee and Wolf, 6000; Servizi _et al._, 6313) but are not very useful due to the complexity of the factors involved in real effluent systems, and the variation of composition of actual effluents from mill to mill (Black, 6301).

Of possible importance are the observations that salmonid fish show avoidance reactions to kraft mill effluents in fresh waters (Jones _et al._, 6310) and that chlorine bleaching of pulps _may_ produce compounds analogous in behavior to the chlorinated hydrocarbon pesticides (Servizi _et al._, 6313). However, recent work by Dr. Carlton Dence has shown, for instance, that chlorophenols exist in only trace amounts in bleach mill effluents (Anon., 6361).

There are a number of ways of treating kraft mill effluents to reduce toxicity. Neutralization of wastes reduced toxicity toward fish (Howard and Walden, 6309). Holding effluents in ponds reduced the BOD considerably (Gehm and Gove, 6307). Dispersion may be effective, but the degree of dispersion necessary for protection of aquatic organisms has not been adequately determined.

Sulfite process:

The sulfite pulping process consists essentially of the digestion of wood chips in the sulfite of calcium, ammonium, or magnesium, usually formed by addition of sulfur dioxide to the appropriate hydroxide. It has not been economically feasible to recycle the calcium and ammonium liquors, but magnesium liquors can presently be recycled, a desirable step from the standpoint of pollution (Waldichuk, 6316; Hall, 6352).

Table 14-3. Toxicity of KME to marine organisms.

Organism	%KME (unless otherwise specified)	Effect	Reference
English sole	8.5	96 hour TL_m	6343
Fluffy sculpin	9	64 hour TL_m at 18‰ and 30‰ sal.	6344
Striped seaperch	9.6	96 hour TL_m	6343
Starry flounder	12.2	96 hour TL_m	6343
Kelp greenling	15.2	96 hour TL_m	6343
Walleye surfperch	est. 5	96 hour TL_m (prelim.)	6343
White seaperch	10.6	96 hour TL_m	6343
Stickleback	12.5	72 hour TL_m	cited in 6344
Salmon, chinook	0.6	growth rate reduced	6299
Salmon, chinook	1.2	30 day critical threshold	6299
Salmon, coho	1.0-3.6	tolerated both bleached and unbleached effluent for 14 days	6299
Salmon, silver	3.3	30 day critical threshold	6299
Salmon, sockeye, young	4.8	tolerated full bleached effluent	6345
Salmon, sockeye, young	2.5	tolerated full bleached effluent at reduced O_2 levels	6345
Dungeness crab	50	no effect on 96 hours exposure	6343
Eastern oyster	0.05	decrease in feeding	6306
Bay mussel, embryos	1.5	48 hour EC50 for strong waste from kraft mill	6342
Bay mussel, embryos	0.52	48 hour EC50	6344
Bay mussel, embryos	0.12	48 hour EC50 for foam collected on a beach near an ocean outfall.	6344

Spent sulfite liquor (SSL) is the term used for the wastes from the digestion process. These wastes are mixed with wash waters and other plant wastes producing an effluent characterized by large volume, very high BOD, high dissolved organic content, and low pH (Eldridge, 6303; McKee and Wolf, 6000).

An average mill uses about 60,000 gallons of water per ton of pulp produced (Hall, 6352). Most of this is wash water, with 2500-3000 gallons per ton being SSL (Eldridge, 6303). Thus, plant effluents contain about 50,000 ppm 10% SSL. The 5-day BOD of the wash-liquor effluent is about 1500 ppm (Eldridge, 6303) while the liquor itself may have 30,000 ppm BOD (Waldichuk, 6316; Anon., 6300). Lignins may make up more than 50% of the dissolved organics in the liquor. The pH of the effluent may be 3-4 (Eldridge, 6303).

The total dissolved solids content of SSL may range from 6% to 16% (Eldridge, 6303). For convenience, all toxicity data are normalized to 10% total solids. Results are then reported as dilutions of 10% SSL. For instance, 10 ppm is 10 parts by volume of 10% SSL mixed with water to make 1,000,000 parts. Another measure of the dilution of SSL is the Pearl-Benson Index (PBI)(Gunter and McKee, 6308). This index is not necessarily correlated with toxicity. It is a measure of the lignin content of the waste waters which may vary from mill to mill. Background levels of natural lignins may vary sufficiently over an area to make accurate determinations difficult (Woelke, 6321).

Sulfite wastes are highly toxic to some marine organisms. Eggs and larvae of oysters, and eggs of English sole were found to be particularly sensitive to SSL (Anon., 6320). Ten ppm was suggested as an upper limit for protection of this kind of aquatic life (Anon., 6320). Toxicities of sulfite wastes to fish are generally lower, in agreement with the observation of McKee and Wolf that BOD presents the major problem with respect to fish (McKee and Wolf, 6000). However, 10 ppm has been shown to affect internal organs of fresh water fish on long exposure (McKee and Wolf, 6000). Acute toxicities to various marine organisms are given in Table 14-4.

Table 14-4. The toxicity of spent sulfite liquor to marine organisms.

Organism	Dilution of 10% SSL (ppm)	Effect	Reference
Salmon, chinook (young)	560-1175	5% mortality	6317
Salmon, chinook	427-757	28 day tolerance level (NH_3-base SWL)	6299
Salmon, chinook	422-616	28 day tolerance level (CaO base SWL)	6299
Salmon, pink (young)	530-1550	5% mortality	6317
Salmon, silver	1015-1230	5% mortality	6317
Oysters, Olympia	10 (Apr -Oct) 20 (Nov-Mar)	recommended safe level	6308
Oysters, Olympia	8-16	harmful	6308
Oysters, Olympia	2-8	reproductive cycle affected, but not necessarily detrimental effect	6312
Oysters, Olympia	7	adverse effect on mortality	6318
Oysters, Olympia	~16	adverse effect on mortality	6318
Oysters, Olympia	8-16	adverse effect on reproduction	6318
Oysters, Olympia and Pacific	13	adverse effect on growth and mortality	6318
Oysters, Pacific (larval)	3	reduction in % normal larvae in laboratory experiments	6318

Organism	Dilution of 10% SSL (ppm)	Effect	Reference
Oysters, Pacific (larval)	7	reduction in % normal larvae (bioassay of natural waters)	6318
Oysters, Pacific (larval)	35	50% abnormal larvae (24°C, 25 $^{o}/oo$)	6302
	26	50% abnormal larvae (20°C, 25 $^{o}/oo$)	
	17	50% abnormal larvae (24°C, 15 $^{o}/oo$)	
Oysters, Pacific (larval)	8-16	threshold of toxicity	6308
Oysters, Pacific (larval)	2	affected	6312
Oysters, Pacific (larval)	18	~ 100% abnormal	6312
Oysters, Pacific	50-100	tolerated	6308
Oysters, Pacific	40 (Apr-Oct) 80 (Nov-Mar)	recommended safe level	6308
Oysters, larval	2-8	4% abnormal	6320
Oysters, larval	<20	50% abnormal (*in situ*) (Everett area)	6320
Oysters, larval	~30	50% abnormal (*in situ*) (Bellingham area)	6320
English Sole, eggs	10	critical threshold for normal development	6320
Monas sp. (oyster food organism)	1000-10,000	lethal	6312
Monas sp. (oyster food organism)	2.5	"depressing effect"	6312

Organism	Dilution of 10% SSL (ppm)	Effect	Reference
Copepods	50-157	significant mortalities in 2 to 14 days	6311
Phytoplankton	50	"significant injury"	6320
Marine food organisms	500	harmful	6317
Fish (marine?)	10	affected internal organs on long exposures	6000
Young herring	599-1022	tolerance level	6311

Groundwood process:

The groundwood pulping process is a purely mechanical process, involving no chemical additives. The wastes include some soluble materials from the wood, but fine wood fibers are the primary contributor to pollution (Waldichuk, 6316; McKee and Wolf, 6000).

Fates of pulp and paper mill effluents:

Hall (6352) states, " Clearly, if pulpmill effluent could be sufficiently diluted, and quickly, in receiving waters of high oxygen content, little trouble would arise..." This statement reflects the feelings of many people associated with the pulp and paper industry waste problem that BOD is the major pollutional concern (McKee and Wolf, 6000). However, it would be unwise to conclude that satisfaction of BOD requirement is the only concern. In particular, the quantities and fates of not readily biodegradable substances, whether natural or added in the pulp and paper making processes, is not known.

The possibilities have only recently started to come to light. Most pulp mill effluents are thought to remain in solution on contacting sea water, with subsequent dispersal and biological and chemical degradation (Schroeder, 6348; Mason and Oglesby, 6349; O'Neal, 6346). However there are indications that under certain conditions some fraction of kraft process effluent precipitates on interaction with sea water (Courtright and Bond, 6344; Føyn, 6347; O'Neal, 6346). In other situations, a fraction of kraft effluent may be foamed off (Courtright and Bond, 6344). Another fraction may be sorbed on any of a number of solid substances (Howard and Walden, 6309; O'Neal, 6346). The nature of the fractions undergoing these various reactions is not well known, but the foamed fraction was shown to have higher toxicity than bulk effluent, even though its PBI was lower (Courtright and Bond, 6344). The possibility that the chlorine bleaching of pulps produces chlorinated hydrocarbons similar in behavior to chlorinated hydrocarbon pesticides and PCB's has been put forth (Servizi et al., 6313) although this suggestion is yet to be confirmed. Moreover, chlorophenols are found in only trace amounts in bleach liquors (Anon., 6361).

In general, the fate of the not readily biodegradable fraction of effluents is unknown. The projected doubling of the pulp and paper industry in the Pacific Northwest in the next 20 years (Hall, 6352) makes it a matter worth investigating.

Summary:

1. There are four pulp and paper mill outfalls into the nearshore marine environment of the Pacific Northwest. They discharge wastes from the production of bleached and unbleached kraft pulp, and kraft paper products.

2. Mill effluents differ significantly in their characteristics. A pollution prevention program, then, should be tailored to a specific plant and location.

3. Acute toxicities of kraft mill effluents to marine organisms are not well known.

4. Toxicities of sulfite mill effluents are better known and suggest a limit of 10 ppm of 10% SSL for protection of marine aquatic life. This represents an approximately 5,000 times dilution of a typical sulfite mill effluent.

5. The amount and final disposition of less biodegradable products of the industry are unknown.

Chapter 15. TRACE METALS IN THE NEARSHORE MARINE ENVIRONMENT

by Stephen W. Hager

The term "trace metals" is not concisely defined. It applies to all elements found in trace quantities (less than 1 mg/l) which show characteristic chemical behavior of metals to a greater or lesser degree. The "heavy metals" and "transition series metals" are both subcategories of trace metals. In all, 54 elements were considered to be trace metals for the purposes of this study.

Use of the term in the text implies a definite lack of specific information, not a generalization over large bodies of data. Where detailed quantitative information is available, the elements for which it is available are specified.

Trace metal pollution is not so spectacular as oil pollution nor so obnoxious as pulp mill effluents. It cannot usually be detected *per se*. Rather, effects on the biology of the area may be the first clue to the fact of pollution. For these reasons, we must be concerned with prevention and early detection of increasing trace metals concentrations.

This study was undertaken: (1) to provide information on existing levels of trace metals in the nearshore marine environment of the Pacific Northwest. The present low level of heavy industrial activity in this area suggests that such data might well be used as a "baseline" for future pollution studies. (2) to collect all data relevant to the distribution of trace elements in the marine environment. From this information it was hoped that an understanding of the behavior of each element in the nearshore environment could be gained which would enable formulation of a meaningful trace metal evaluation program in the Pacific Northwest. The following discussion attempts to point out information necessary for a consideration of coastal pollution by trace metals.

Chemical Form

Chemical forms of trace elements in sea water must be known before an evaluation of their pollution potential can be made. Oxidation state and physical state are equally important. The oxidation states of many trace metals in sea water are reasonably well known, either by inference from thermodynamics or by direct observation.

It should be noted that thermodynamic estimates and observational data sometimes conflict, as in the cases of arsenate and arsenite (Goldberg, 6059), chromium (III) and chromate (Fukai and Huynh-Ngoc, 6269), and others. In such cases, the disagreements have been attributed to a need for reaction sites (Goldberg, 6059), organic counter-reactions (Fukai and Huynh-Ngoc, 6269), or analytical problems. It seems possible that this problem might arise for other elements.

Adsorption or particulate matter and chelation by dissolved organic substances are processes which may control the concentration of a trace metal in sea water. The quantitative partitioning between these reservoirs and the dissolved ionic fraction is largely unknown. We distinguish between particulate (>0.45μ) and soluble material, but this is an operational definition, related in an unknown way to the actual manner in which the metal behaves.

Table 15-1 presents data on the chemical and physical states of trace metals in sea water with appropriate references. In cases where there is substantial agreement between investigators, only the most recent is cited.

Table 15-1. Predominant physico-chemical forms of trace elements in sea water compiled from the literature.

Element	Physical Form	Chemical Form	References
Al	particulate	---	6139
	---	$AlO_2^- (H_2O)$	6075
Sb	ionic (?)	SbO^+ (?)	6061
	---	$Sb(OH)_6^-$?	6363
As	ionic	H_3AsO_3, H_3AsO_4	6060
	---	$HAsO_4^=$, $H_2AsO_4^-$	6059
	---	H_3AsO_4, H_3AsO_3	
Ba	---	Ba^{++}, $BaSO_4$	6059
	ionic	---	6035
Be	"soluble"	---	6112
	particulate (?)	---	6019
Bi	ionic	BiO^+ (?)	6102
Cd	ionic	$CdCl^+$, $CdCl_2$	6102
	---	Cd^{++}, $CdSO_4$	6059
	---	$CdCl^+$	6099

Table 15-1 continued

Element	Physical Form	Chemical Form	References
Cs	---	Cs^+	6059
	ionic	---	6019
Cr	particulate (?)	Cr^{+++}	6269
	ionic	$CrO_4^=$	6269
Co	---	Co^{++}	6059
	ionic	---	6019
Cu	soluble	Cu^{++}	6192
Ga	soluble (?)	$Ga(OH)_4^-$	6180
	particulate (?)	---	6019
Ge	---	$Ge(OH)_4$	6059
	particulate (?)	---	6019
Au	---	$AuCl_4^-$	6059
	particulate	---	6109
	ionic	---	6019
Hf	---	HfO^{++}	6179
In	---	In^{+++} (?)	6143
	---	$In(OH)_2^+$	6285
Fe	---	$Fe(OH)_3$ (soluble)	6059
	soluble, particulate	---	6193
Pb	soluble, particulate	Pb^{++}	6160
	ionic	---	6019
	---	Pb^{++}, $PbOH^+$, $PbCl^+$	6363
Li	ionic	Li^+	6034
Mn	particulate	---	6109
	ionic	Mn^{++}	6110

Table 15-1 continued

Element	Physical Form	Chemical Form	References
Hg	soluble	Hg^{++}	6071
	ionic	$HgCl_3^-$, $HgCl_4^=$	6059
Mo	---	$MoO_4^=$	6059
	ionic	---	6102
Ni	---	Ni^{++}	6059
	ionic	---	6177
Nb	particulate (?)	NbO_2 (soluble) (?)	6027
Pd	unknown	---	---
Pt	unknown	---	---
Po	---	$Po(OH)_4$ (?)	6179
Re	---	ReO_4^-	6140
Rb	ionic	Rb^+	6059
Ru	mostly ionic	(?)	6028
Sc	---	Sc^{+++}	6075
	particulate (?)	---	6019
Se	---	$HSeO_3^-$	6030
	---	$SeO_4^=$	6059
Ag	---	$AgCl_2^-$	6102
	ionic	---	6019
Sr	---	Sr	6059
	ionic	---	6019
Tl	ionic	Tl	6144
Sn	ionic	SnCl (?), $SnCl_3^-$ (?)	6179
	particulate (?)	---	6019

Table 15-1 continued

Element	Physical Form	Chemical Form	References
Ti	particulate (?)	H_4TiO_4	6062
W	---	$WO_4^{=}$	6059
	ionic	---	6102
V	---	$H_2VO_4^{-}$, $VO_2(OH)_3^{=}$	6102, 6059
	ionic	---	6019
Y	particulate (?)	$Y(OH)_3$ (soluble)	6117
Zn	ionic	Zn^{++}	6117
	---	Zn^{++}; $ZnOH^{+}$	6099
Zr	particulate (?)	---	6061

(?) indicates speculative

The problem of possible trace metal pollution of the nearshore marine environment of the Pacific Northwest may be considered to be a "flushing" or "residence time" problem.

The important factors are input rates, output rates, and allowable residual levels. Input rates include both those from natural and industrial sources. Output rates include those effected by circulation and by biogeochemical processes. Allowable residual levels are those concentrations, resulting from the balance of inputs and outputs, which do not constitute pollution.

Natural Inputs

There are three major natural inputs of water containing trace metals to the nearshore areas of the Pacific Northwest; surface advection, upwelling, and land drainage/rivers.

Advection of surface water trace metals into the area of interest is the "background" input against which the other inputs, upwelling and land drainage, operate. The magnitude of the effects of the other inputs will depend to a large extent on the rate of this advective input which is discussed in Chapter 9.

Trace metal concentrations in the advecting waters are poorly known. Gold and iron are the only trace metals which have been determined in the nearshore waters (0-10 km) of the Pacific Northwest. Caldwell ([illegible]5) found an average value of 0.21 μg gold/l in seven samples taken at Waconda Beach, just south of Waldport, Oregon. He detected less than 0.05 μg gold/l at Agate Beach, north of Newport, Oregon. Putnam (6132) found 5.1 μg gold/l at Copalis Beach, Washington, and less than 0.5 μg gold/l at Bandon, Oregon. Strickland (6156) found 8.4-16 μg/l total reactive iron on the Washington coast.

A determination of molybdenum at Muir Beach, Marin County, California, is perhaps relevant, although not strictly in our survey area. Bachmann and Goldman (6008) found 10.0 μg molybdenum/l.

The elements aluminum, arsenic, cobalt, copper, iron, lead, manganese, nickel, selenium, and titanium have been determined for the waters of Puget Sound, the Strait of Juan de Fuca, and the Northeast Pacific, but these measurements may not be representative of the open nearshore coastal environment.

Measurements of nearshore and oceanic trace element concentrations suitable for direct comparison have been made for eight elements (Table 15-2). Six of the elements compared give values which might be explained by considering the mixing of sea water and land drainage water (see Table 15-5). However, data are insufficient to permit generalizations about concentrations to be expected in nearshore areas.

A compilation of probable values for various trace metals in nearshore and oceanic waters is presented in Table 15-3. The values given result from a consideration of the frequency distribution of all values available (see Appendix 4). Other factors considered were location, proximity to land masses, methods, season, and depth. References are for representative studies.

Previous compilations of oceanic trace metal concentrations have been made by Richards (6261), Goldberg (6058), (6059), (6290), Høgdahl (6289), Riley (6181), and Bowen (6019).

The trace metal concentrations considered in this compilation may be real and a result of various hydrologic, geologic, and biologic

Table 15-2. Direct comparisons of nearshore and oceanic values for trace metals

Element	Nearshore Value (Location)	Open Oceanic Value	Reference
Al	2 ± 1 μg Al/l (ionic) (Scripps Pier)	1 ± 1 μg Al/l (ionic)	6139
Be	1.7×10^{-4} μg Be/l (soluble) 0.9×10^{-4} μg Be/l (particulate) (Scripps Pier)	3.9×10^{-4} μg Be/l (soluble) 1.8×10^{-4} μg Be/l (particulate)	6112
Cs	0.335 ± 0.012 μg Cs/l (Scripps Pier)	0.35 ± 0.024 μg Cs/l	6052
Cu	ca. 20 μg Cu/l (tropical waters)	ca. 10 μg Cu/l	6192
Fe	up to 25 μg Fe/l (tropical waters)	as low as 0.5 μg Fe/l	6194
Fe	8.4 - 16 μg Fe/l (total reactive) (Washington coast)	4.6 μg Fe/l (total reactive)	6156
Mn	up to 3.9 μg Mn/l (Gulf of Mexico)	as low as 0.2 μg Mn/l	6137
Rb	170, 190 μg Rb/l (Caribbean)	120, 120, 140 μg Rb/l	6014
Sr	5.5 mg Sr/l	7.5, 7.8, 7.0 mg Sr/l	6014

Table 15-3. Probable values of trace metals in oceanic and nearshore waters

Element	Form Measured	Oceanic Concentration µg/l	Nearshore Concentration µg/l	Reference(s)
Al	dissolved (ionic)	1 ± 1	→10	6139
	total <0.45µ	<10	---	6139
	particulate	1 - 120	→10,000	6139
Sb	total	0.33	---	6141
	total	---	0.3	est
As	total	---	1 - 7	6177, 6077
	total	2 - 3	---	6149, 6128
	total	15 - 37	---	6060, 6164
Ba	total	13	---	6016, 6035
	total	---	13	est
Be	soluble	0.00039	0.00017	6112
	particulate	0.00018	0.00009	6112
Bi	total	0.033	---	6130
	total	---	0.03	est
Cd	total	0.11	0.11	6118, 6091
Cs	total	0.35	0.335	6052
Cr	dissolved (total)	0.4	0.3 - 0.6	6274
	particulate	0.03 - 0.012	---	6272
	Cr(III)	0.2	→0.2	6274
	Cr(VI)	0.2	0.1 - 0.4	6274
Co	total	0.27(0.035-4.1)	---	6141
	total	---	0.2 - 0.7 ?	6163, 6177

Table 15-3. continued

Element	Form Measured	Oceanic Concentration μg/l	Nearshore Concentration μg/l	Reference(s)
Cu	ionic	0.3 - 2	---	6192, 6193
	ionic	---	→5	6037, 6040
	total <0.5μ	→20	---	6192, 6193
	total	---	→600	6195
	particulate	<0.5	---	6192, 6193
Ga	total	0.03	---	6023
Ge	total	0.06	0.06 ?	6023
Au	total	0.011	---	6141
	total	---	→5 ?	6132
Hf	total	<0.008	---	6141
In	ionic	<0.012 (inferred)	---	6285
Fe	total <0.5μ	0 - 6	---	6108, 6162
	total <0.5μ	---	→25	6176, 6105
	ionic	<1	---	6193
	particulate	0 - 5	---	6094, 6108
	particulate	---	→100	6176, 6105
	total	---	→200+	6164
Pb	total	0.03 - 0.3	---	6160
	total	---	→1.5	6109
Li	total	170 - 180	---	6034, 6136
Mn	total	0.2 - 4	---	6137, 6050
	total	---	→10	6165
Hg	total	0.08 - 0.15	---	6065

Table 15-3. continued

Element	Form Measured	Oceanic Concentration µg/l	Nearshore Concentration µg/l	Reference(s)
Mo	total	10	---	6172, 6186
	total	---	10	6008, 6209
	total	0.8	---	6189
Ni	total	5.4 (0.43-43)	---	6141, 6055
	total	---	<6	6104, 6193
Nb	total	<0.005	→0.1	6027
Re	total	0.0084	---	6140
Rb	total	120	---	6153, 6016
	total	---	→400	6014, 6078
Sc	total	<0.004	---	6141
Se	total	0.05 - 0.5	---	6141, 6030
	total	---	→6	6077
Ag	total	0.29 (0.055-1.5)	→19.6	6141
Sr	total	6 - 10	---	6038, 6197
	total	---	5 - 12	6014, 6096
Tl	total	<0.01	---	6121, 6144
Sn	total	0.30 - 1.22	---	6067
Ti	total	8 - 9	---	6015
	total	---	<6	6015, 6062
W	total	0.09 - 0.12	---	6077, 6087
V	total	1 - 5	---	6089, 6029
	total	---	5 - 7	6015

Table 15-3. continued

Element	Form Measured	Oceanic Concentration µg/l	Nearshore Concentration µg/l	Reference(s)
Y	total	0.3	---	6075
Zn	total	0.6 - 25	---	6155, 6175
	total	---	→40	6189, 6114
Zr	total	0.011 - 0.041	---	6145

→ Signifies highest measured value

est Signifies estimated from trends in behavior, but not based on actual measurements

? Signifies great uncertainty in the value(s) cited

processes, or they may be analytical artifacts. Often, it is impossible to decide which the case may be. No attempt was made, therefore, to exclude outlying results from consideration. Where the results of one investigator had been criticized by a subsequent investigator on the grounds of the methods involved, however, this was considered.

Upwelling may provide the single largest perturbing influence on trace metal concentrations off our coast. Schutz and Turekian (6141) found that silver, cobalt, and nickel were significantly higher in areas of upwelling. However, they did not state whether upwelling was actually occurring at the time of sampling. Concentrations of aluminum, chromium, copper, iron, gallium, lead, titanium, and zinc, all with high concentration factors in plankton (Table 15-4), might be higher in upwelled waters.

Land drainage probably does not play a significant role in determining the dissolved trace metal concentrations on our coast. As can be seen from Table 15-5, the concentrations of many trace metals in the river waters are roughly similar to those in sea water. Thus, the change in the salinity of a sample of mixed river-sea water environment would be much greater than the change in the trace metal

Table 15-4. Concentration of trace metals by plankton: concentration factor = ppm in fresh organism/ppm in sea water. (Concentration factors from 6019.)

Element	Concentration Factor	Comment
Ag	210	
Al	25,000	Marine organisms may be able to utilize particulate Al, making this number of doubtful meaning.
Ba	120	Based on a sea water value of 30 ppb. Surface water value is probably around 13 ppb.
Cd	910	
Co	4600	
Cr	17,000	Based on a S. W. concentration of 0.00005 ppm. It appears that 0.0005 ppm may be more reasonable, giving a concentration factor of 1700.
Cs	1-5	Based on a sea water value of 0.05 ppb. Value is probably nearer to 0.3 ppb.
Fe	2000-140,000	See comment on Al.
Ga	12,000	See comment on Al.
Mn	750-9400	
Mo	25	
Ni	1700	Nickel concentrations in S. W. show great variation 0.43 to 43 μg/l in one worldwide study (6141).
Pb	41,000	Based on deep water Pb value of 0.03 ppb. 0.1 to 0.3 ppb is probably a better surface value.

Table 15-4. continued

Element	Concentration Factor	Comment
Ru	600-3000	
Sb	50	
Sn	2900	Value is based on a sea water value of 3 μg/l (6121). Sea water value may be around 1 μg/l (6067).
Sr	8, 9	
Ti	20,000	
V	620	
Zn	1000-65,000	
Zr	1500-3000	

Table 15-5. Comparison of trace element concentrations in rivers and in sea water

Element	Rivers[1] μg/l	Columbia River[2] μg/l	Sea water[3] μg/l
Al	130	90	1-10
Sb	1.1	--	0.3
As	2	2	2-3
Ba	44	32	13
Be	0.01	<0.03	0.0004
Cd	0.24	<0.2	0.11
Cs	0.02	--	0.35
Cr	3.2	2	0.3-0.6
Co	0.3	0.02	0.2-0.7
Cu	10	10	1-10
Fe	40	30	0-6
Pb	4.2	3.2	0.03-0.3
Li	1.1	2.2	170-180
Mn	25	1.5	0.2-4
Hg	0.08	--	0.08-0.15
Mo	8	6	10
Ni	7	<23	5.4
Rb	1.3	<1.2	120
Se	0.20	--	0.05-0.5
Ag	0.19	0.12	0.29
Sr	80	62	6-10
Sn	0.04	∿0	0.3-1.2
Ti	8.6	3.4	8-9

Table 15-5. continued

Element	Rivers[1] μg/l	Columbia River[2] μg/l	Sea water[3] μg/l
V	1	~2	1-5
Zn	10	20	0.6-14
Zr	2.6	~0	0.011- 0.041

[1] Durum and Haffty (6281)
Livingstone (6283)
Kopp and Kroner (6278)
Kharkar, Turekian, and Bertine (6282)

[2] Durum and Haffty (6284)
Kopp and Kroner (6278)
Silker (6045)

[3] This review

concentrations. Aluminum, beryllium, chromium, iron, lead, manganese, strontium, and zirconium apparently have significantly higher concentrations in river waters than in sea water.

All of these inputs undergo seasonal cycles. Ambient nearshore trace metal concentrations may be highest following winter periods of low productivity (Atkins, 6007; Chow and Thompson, 6037). River inputs are probably highest at the times of highest runoff, although river concentrations of trace metals may be highest at times of lowest runoff (see Chapter 4). Upwelling occurs primarily in the late spring, summer, and early fall, although winter occurrences have been observed (Burt, McAlister, and Queen, 6329). The net effect of these variations may be to reduce the seasonal variations in the sea water, while intensifying short term and local variations.

Industrial Inputs

One ultimate goal is to quantitatively estimate the rate of input of potential pollutants which a given area can tolerate. In order to do this, we must know the characteristics of the proposed effluent. These data should include estimates of maximum volume of effluent to be expected and maximum concentrations of various substances which will occur in the effluent. Plans for such a waste inventory on a national scale are presently beset with implementation difficulties (Anon., 6358). Such declarations are regularly required by the Department of Environmental Quality of the State of Oregon and the Water Pollution Control Commission of the State of Washington (Anon., 6356). The California Regional Water Quality Control Boards require only a general "type of waste" declaration, with the stipulation of "... such additional information as it (the regional board) deems necessary." (Anon., 6357). Each proposal is treated as a separate case.

Removal Processes

A number of authors have adequately outlined the processes by which trace metal pollutants may be removed from nearshore marine waters(Waldichuk, 6284; Carritt and Harley, 6028). These processes include advection, biological activity, sorption, flocculation, ion exchange, precipitation and coprecipitation (Waldichuk, 6284). However, research on removal mechanisms has progressed little beyond the naming of the various possible mechanisms. There are almost no quantitative data. In short, then when asked to predict the fate of additions of toxic trace metals to nearshore waters of the Pacific Northwest, we must answer, "we don't know."

The reasons for this ignorance are several. First, the nearshore coastal zone is very complex. The processes of removal of trace metals vary in time and space. A measurement in the summer may not be applicable to the winter; a measurement in Southern California may not be applicable to Northern California.

Second, the necessity for understanding the processes has not always been clear. Much pollution prevention has, in the past, actually been pollution correction. Admittedly, the prediction of pollution is not always possible, as, for instance, in the cases of the biological production of methyl-mercuryand the worldwide dispersal of DDT. However, as our technology rapidly advances, we must attempt to predict environmental consequences, since they may be only slowly reversible. In particular, trace metals in sediment and biological reservoirs may continue to supply pollutant long after the original source has been removed (Anon., 6337; Abelson, 6338).

What is needed, as specified by Carritt and Harley (6028) for radionuclides, is sufficient information on assimilative processes to be able to construct balance sheets, accounting for all of each specific pollutant added. For example, the study of Duke et al. (6325) showed that of the zinc-65 added to experimental ponds, up to 98.8% was found in the sediments, 0.2% in the macrobiota, and 0.0% in the water at approximately steady state conditions. Although it will not be economically feasible to do the same with all industrial effluents, it is essential that we recognize such complete knowledge as an ideal, and that we not lose sight of that ideal.

Precisely what do we know, relevant to the nearshore waters of the Pacific Northwest?

Advective Removal

The advection of nearshore waters of the Pacific Northwest is not well enough known to allow its quantitative prediction for a specific site (see Chapter 9). Generally, the advecting waters will remove the dissolved fraction of the trace metal from an area. In addition, portions of other fractions (sorbed, precipitated, or flocculated) may be removed. Consequently, advection will probably be a key concern in outfall siting. The greater the rate of advective flow out of an area, the lower the amounts of pollutant remaining in the area under steady state conditions.

However, the metals may be removed from the water before it can be advected from the nearshore zone. This may be accomplished by biological or geochemical processes which may act to prevent acute pollution by removing metals from the solution phase or to establish chronic pollution by concentrating the pollutant in another form and in another place.

Biological Removal

Net removal of trace metals by biological means depends on several factors: a) primary production by phytoplankton, b) transportation of organic matter by physical processes, c) destruction of organic matter by organisms or non-biological processes, and d) rate of inorganic sedimentation (Gross, 6122).

The surface sediments of the Pacific Northwest inside of 10 km are generally characterized by large particle size (sand) and low organic matter content (0.1%)(Bushnell, 6148; Carey, 6134). Thus, although production in areas of upwelling may be as high as 150 $gCm^{-2}yr^{-1}$ (60 $gCm^{-2}yr^{-1}$ is average for the area, Gross, 6122), the net removal of organic material in the nearshore region is probably low. However, high concentrations of glauconitic sands (up to 90%), and organic carbon (up to 3%) in sediments from the continental slope about 30 miles offshore (Bushnell, 6148) suggest that transport and deposition of organic material away from the coast may be significant

Substantial burial of organic material by rapid sedimentation is not probable due to the well-sorted characteristics of the nearshore sediments (Bushnell, 6148).

Biological processes have been implicated in the removal of barium (Goldberg, 6169), copper (Turekian, 6125), vanadium, tungsten, cobalt, and nickel (Krauskopf, 6102), and cadmium (Brooks and Rumsby, 6021).

Geochemical Removal

Geochemical removal processes include precipitation, complexing and chelation, and solid-ion interactions such as sorption, ion exchange, flocculation, and coprecipitation.

Precipitation: It is doubtful that solubilities of inorganic precipitates control the concentrations of many elements in sea water (Goldberg, 6059). However, precipitates formed by the reaction of an effluent with sea water may occur, and it is this process which is of interest in considering coastal pollution. The precipitates formed may act as transport mechanisms and later redissolve producing no net removal from sea water. However, by this process mass removal of pollutants from nearshore areas or accumulation of the material in nearshore areas may occur.

The main precipitates which might be formed by trace metals in sea water are carbonates and hydroxides or hydrous oxides. Carbonates of cobalt, copper, zinc (Goldberg, 6059; Duursma and Sevenhuysen, 6213), and lead (Goldberg, 6059) might be precipitated from sea water of pH 8 at levels around 20 μg/l.

Copper hydroxide might also be precipitated from pH 8 sea water at around 20 μg/l (Duursma and Sevenhuysen, 6213). There is great uncertainty in these estimates. The pH dependence of these precipitations is inherent in the anions involved. Associations with inorganic ligands and dissolved organic substances in sea water may also alter these estimates considerably. Kinetics of precipitation will probably be unimportant due to the availability of nucleation surfaces (particulate matter) in nearshore waters.

Complexing: Complexing by inorganic ligands does not physically remove metals from the environment. It does change their ionic form, however, which affects their geochemical behavior and possibly their toxicity. The major ligands are the chloride and sulfate ions which are present in consistently large quantities in sea water. Carbonate ions may also be important. Recent studies have indicated that some trace metals may form ion pairs with the inorganic anions of sea water. Specifically, there is evidence for hydroxyl or carbonate ion pairs of zinc and lead in sea water (Zirino and Healy, 6275).

Chelation: Chelation of metals by the dissolved organic substances in sea water is known to occur (Koshy and Ganguly, 6339; Williams, 6040; Barsdate, 6279; Rona et al., 6137), but the conditions under which this process occurs in the natural environment are not well known (Barsdate, 6279; Koshy and Ganguly, 6339). The major effect is "solubilization," or a tendency to keep metals in the soluble ($<0.45\mu$) fraction of a sea water sample(Koshy and Ganguly, 6339). Chelation thus affects the behavior of a metal with respect to removal processes such as precipitation and sorption. The organic ligands which chelate metals in sea water are unknown.

The quantity of dissolved organics in nearshore waters of the Pacific Northwest is unknown. As shown by Duursma (6341), the factors determining dissolved organic concentrations are insufficiently known to allow prediction of the levels by considering the area to be a typical nearshore, upwelling, high-productivity area.

Solid-ion interactions: The reaction of trace metal ions with solid materials in sea water may result in the removal of the ions from solution. The extent to which this process is capable of removal of added metals from sea water will be determined primarily by the form of the ions involved and by the nature and amount of solids involved.

The nature of the ions of concern will be determined by the composition of the effluent, and its immediate interactions with sea water. Such interactions may include inorganic complexing or organic chelation.

The solids which interact with metal ions in sea water are extremely varied, including organic detritus, inorganic mineral grains, hydrous oxide flocs, precipitates, etc. In addition, each of these descriptive terms may encompass a wide range of materials with equally widely varied sorptive characteristics. Even for relatively well defined substances, factors such as previous history can change sorption behavior. Thus, this discussion will deal only with the general category solid materials.

Of the number of ways of considering solid-ion interactions which may occur in sea water, the concept of reservoirs (see Carritt and Goodgal, 6266) seems to be most useful. Although simplistic, it provides a quantitative overview conspicuously lacking in some other approaches. Although there are few real numbers which we can use in this model to get useful answers, the types of data needed will be made evident.

A schematic of a simple two-reservoir system is shown in Figure 15-1.

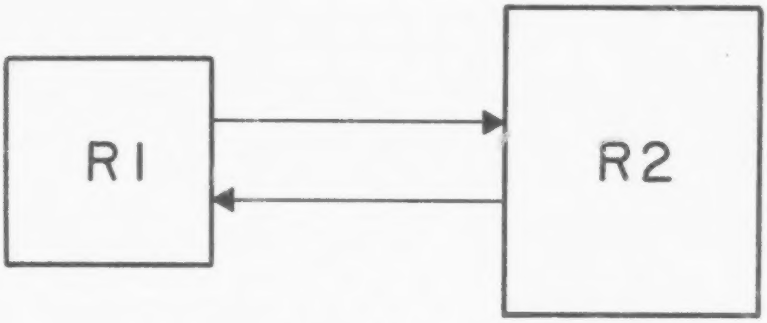

Figure 15.1.

The system can be roughly described by a distribution coefficient between the two reservoirs, and by the sizes of the two reservoirs. It is the latter factor which is often neglected.

4. K_D may depend on X_s or C_w, although within reasonable limits of X_s dependence does not seem great (Duursma and Bosch, 6330). At low solution concentrations, however, K's varied with solution concentration (Hamaguchi, 6335).

5. K_D and X_s are operational parameters. For instance, if C_s and C_w are defined as the concentrations in the fractions which are retained and which pass through a 0.45μ filter, respectively, f_s is then the fraction sorbed on the greater than 0.45μ fraction, and thus represents a lower limit to the material actually sorbed.

6. Organic chelation and sorption can change the entire system, emphasizing the need to use natural waters and sediments.

The shaded area in Figure 15-2 represents that bounded by reasonable K_D (10^2-10^5) (Duursma and Bosch, 6330; Ganapathy, Pillai, and Ganguly, 6365) and reasonable X_s (10-1000 mg/kg) (Ganapathy, Pillai, and Ganguly, 6365) values. Note that the f_s values range from about .99 to 0.001, or from 99% of the metal sorbed on the sediment of 0.1% sorbed. This uncertainty again outlines the necessity of data specific to the region of interest and the element of interest, using K_D's and X_s's observed in the waters into which the proposed effluent will flow.

Although it appears that the suspended material in sea water is qualitatively superior to the consolidated sedimentary material with respect to sorptive capacity (due to particle size) and availability (due to dispersion in the water column), the major limitation on the suspended material will be quantitative. That is, while the suspended materials will, in general, have a higher sorptive capacity per gram and will be more likely to come in contact with the ions, the total sorptive capacity (capacity per gram times gram available sorbent) may not be sufficient to remove significant amounts of trace metals.

Therefore, although we do not presently have sufficient knowledge of turbulent diffusion and mixing to determine which effluents will be brought into direct contact with bulk sediment (see Chapter 11), this distinction will be, as pointed out by Waldichuk (6284), an important one. There seems to be little doubt that metals in effluents which come into contact with bulk sediments will become sorbed to a substantial degree (Pritchard, 6231; Duke, Willis, and Price, 6325; Carritt and Goodgal, 6266; Postma, 6331; Duursma and Bosch, 6330). This is borne out by a consideration of Figure 15-2. At a sediment-water interface, we can probably say that X_s increases greatly, although, as pointed out in consideration number 3, it becomes difficult to quantitatively define.

A trace metal pollutant may be partitioned between reservoirs such as suspended material, consolidated sediments, dissolved components, and biota. The biological reservoir has already been discussed in part.

In order to get some quantitative feeling for the partitioning of a trace metal between the dissolved and suspended reservoirs, consider Figure 15-2 which is derived from mass balance considerations. T is the total trace metal in the water-suspended material system, C_s is the concentration of the metal on the suspended material, X_s is the concentration of suspended material in the water, M_w is the mass of water being considered, C_w is the concentration of the trace metal in the water, f_s is the fraction of the total trace metal which will be found associated with the particulate matter, and K_D is the distribution coefficient for the metal between the particulate matter and the water, defined as C_s/C_w.

As mentioned above, such a diagram is only able to give a feeling for the possible magnitude of some of the factors involved and cannot and must not be used without consideration of these approximations involved in its derivation:

1. It is assumed that the water and suspended material are the only two "reservoirs" involved. A similar diagram could be made for the relationship between amounts of metal in water and in the biota. The vertical axis would be biomass concentration in the water and the horizontal axis the concentration factor (see Table 15-4) for a given metal. Thus, only if other reservoirs are small when compared to the suspended material reservoir can we use Figure 15-2.

2. Obviously, this is an "equilibrium" model. Whether or not this is a realistic model of the natural environment is now known. In particular, the reversibility of sorption reactions is not well known. Thus metals sorbed in one ionic environment and transported to another may or may not be desorbed (Turekian, 6282; Johnson, Cutshall and Osterberg, 6047; Kharkar, Turekian and Bertine, 6215).

3. The diagram cannot be used for waters in contact with bulk sediments. The model is very sensitive to variations in X_s, which would be difficult to define in such a case.

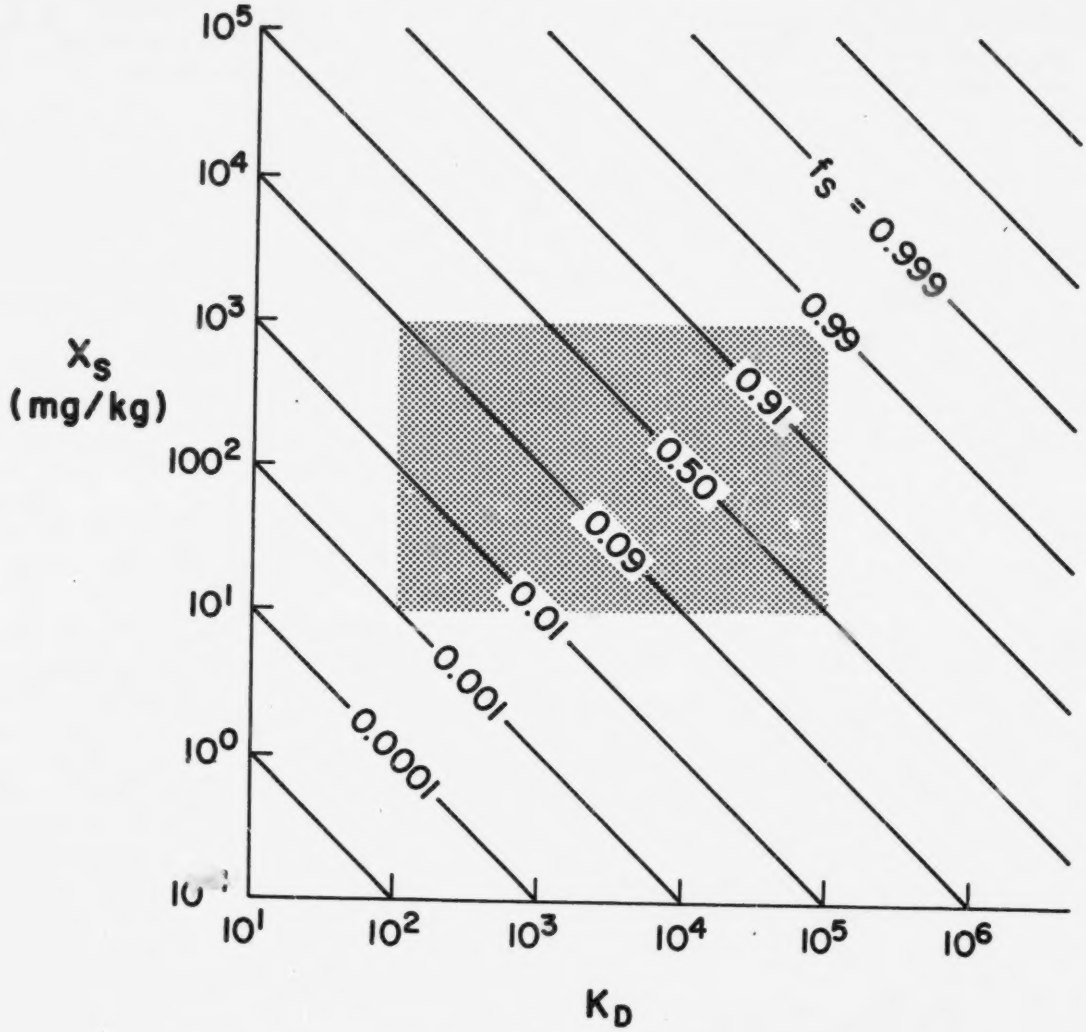

Figure 15-2. Nomograph representing approximate partitioning of a metal between dissolved and suspended particulate reservoirs. X_s, concentration of suspended material in the water in mg/kg; K_D, observed distribution coefficient for a specific metal on a specific material; f_s, fraction of metal in water-suspended material system sorbed on suspended material. $T = C_sX_sM_w + C_wM_w$. $F_s = \frac{C_sX_sM_w}{T} = \frac{K_dS_s}{K_dX_s+1}$

It was noted earlier that the nearshore sediments of the Pacific Northwest are primarily well-sorted sands (X_s very large; K_D small). Much less is known, however, about the suspended material; its quantity (X_s), its characteristics (K_D), its sources and sinks, and its rate of passage through the nearshore area. The quantity of suspended material in nearshore areas of the Pacific Northwest is thought to be high (Waldichuk, 6284). Areas affected by the river drainage might be expected to be particularly high.

Not much is known about the characteristics of the nearshore suspended material. It might be guessed that suspended particulate matter is primarily organic in the spring and summer months and inorganic during the winter months, but this is unconfirmed. A median diameter of 2 to 3 microns has been observed (Carder, 6353), suggesting that the surface to mass ratio would be high, and that a high sorptive capacity would exist. In addition, the Stokes' settling rate for particles of this size would be about 70 cm/year, resulting in negligible sedimentation as compared to advection into deeper waters. The observed distribution of sediment sizes in nearshore sediments bears this out (Bushnell, 6296).

Allowable Residual Level

The establishment of allowable upper limits for trace metal concentrations in nearshore waters will require criteria for distinguishing between change, and detrimental change (pollution). The "no change" approach is rejected *a priori*, since if we detect no change it could mean simply that we are looking at the wrong variables or with insensitive techniques.

There are a number of approaches which one might take in order to determine permissible trace metal concentrations in nearshore areas. They include consideration of (1) the lethal limits and sub-lethal effects for individual species, (2) lethal concentrations and sub-lethal effects for natural populations, and (3) ecological models.

Individual species: Most studies aimed at determining the permissible levels of a toxic substance in the marine environment have determined the tolerance of certain species of organisms to that substance. The toxicities of various trace metals to marine organisms found in the Pacific Northwest are presented in Table 15-6. The data are listed alphabetically by species under the appropriate metal. Included are the concentration and form of the metal, effect on the organism, duration of the exposure, and the pertinent literature citations. Data for additional marine species are presented in Appendix 4. Reviews

Table 15-6. Response of marine organisms of the Pacific Northwest to various concentrations of trace elements

Generic name trace element concentration	Specific name (common name) effect on the organism (TL_m, killed, not lethal)	duration of test	Reference No. other factors
Al	*Crassostrea virginica* (oyster)		6207
88 ppm	not toxic	11 days	$AlCl_3$
As	____________ ____________ (pink salmon)		6004
5.3 mg/l	"extremely harmful"	8 days	As_2O_3
Cd	*Crassostrea virginica* (oyster)		6004
0.2 mg/l	TL_m	8 weeks	$Cd(NO_3)_2$
0.1 mg/l	TL_m	15 weeks	$Cd(NO_3)_2$
	Mya arenaria (soft-shell clams)		6131
0.1 ppm	apparently not toxic	56 days	----
Cl_2	*Crassostrea virginica* (oyster)		6000
0.01-0.05 mg/l	pumping activity reduced		----
1 mg/l	effective pumping impossible		----
	Macrocystis pyrifera (giant kelp)		6000
1.0 mg/l	no effect	5 days	----
5-10 mg/l	10-15% photosynthesis reduction	2 days	----
5-10 mg/l	50-70% photosynthesis reduction	5-7 days	----
	Mytilus edulis (adult mussel)		6243
10 ppm	killed	5 days	----
2.5 ppm	killed	5 days	----
1 ppm	killed	15 days	----

Table 15-6. continued

Cr	*Macrocystis pyrifera* (giant kelp)			6000
	1 mg/l	photosynthesis diminished	5 days	$K_2Cr_2O_7$
	Nereis virens (polychaete worm)			6203
	1 ppm	threshold	5 weeks	Cr^{+6}
	Nereis virens (polychaete worm)			6004
	0.2 mg/l	similar to controls	20 weeks	$Cr_2O_7^=$
Cu	*Acartia clausi* (copepod)			
	0.5 mg/l	50% mortality	13 hours	citrate
	Acmaea scabra var. *limatula* (mollusc)			6255
	0.10 ppm	lethal	3 days	----
	Balanus crenatus (adult barnacles)			6236
	10 mg/l	killed	2 hours	$CuSO_4$
	Balanus crenatus (barnacle nauplii)			6236
	30 mg/l	killed	2 hours	$CuSO_4$
	Haliotis fulgens (mollusc)			6255
	0.10 ppm	100% mortality	3 days	----
	0.05 ppm	less than 100% mortality	30 days	----
	Ischnochiton conspicuus (mollusc)			6255
	0.15 ppm	100% mortality	10 days	----
	0.10 ppm	less than 100% mortality	60 days	----
	Macrocystis pyrifera (giant kelp)			6000
	0.1 mg/l	visible injury	10 days	$SO_4^=$ & Cl^-
	0.1 mg/l	50% photosynthesis inhibition	2-5 days	$SO_4^=$ & Cl^-
	Mya arenaria (soft-shell clam)			6131
	0.02 ppm (0.05 ppm	least toxic concentration studied	8 days	Cu^{++}

Table 15 -6. continued

Cu	*Mytilus californianus* (mussel)			6255
	0.20 ppm	100% mortality	2 days	----
	0.15 ppm	less than 100% mortality	30 days	----
	0.10 ppm	less than 100% mortality	60 days	----
	Mytilus edulis (mussel)			6238
	0.55	killed	12 hours	citrate
	0.14	killed	1 day	citrate
	0.08	killed	2 days	citrate
	0.04	some mortality	3 days	citrate
	0.02	no mortality	4 days	citrate
	Mytilus edulis (mussel)			6255
	0.20 ppm	100% mortality	17 days	----
	0.10 ppm	less than 100% mortality	35 days	----
	Mytilus edulis (mussel)			6000
	0.32 mg/l	"significant response"	----	$SO_4^=$
	Mytilus edulis planulatus Lamarck (bivalve mollusc larvae)			6247
	22.2 mg/l	50% mortality	2 hours	citrate pH 7.0-8.2
	Neosphaerona oregonensis (isopod)			6000
	0.02 mg/l	"significant response"	----	$SO_4^=$
	Nereis virens (polychaete worm)			6203
	0.1 ppm	threshold	21 days	----
	Paphia staminea var. *laciniata* (mollusc)			6255
	1 ppm	non lethal	30 days	----
	3 ppm	∿50% lethal	∿60 days	----
	Skeletonema costatum (phytoplankton)			6240
	0.20 ppm	toxic (no growth)	8 days 20 °C	$SO_4^=$
	0.17 ppm	toxic (no growth)	8 days 30 °C	EDTA, cultured, static, bacterially contaminated

Table 15-6. continued

Cu	Spirorbis lamellosa Lamarck (tubeworm larvae)			6247
	0.51 mg/l	50% mortality	2 hours	citrate pH 7.0-8.2
	Staphlococcus aureus (bacteria)			6253
	18 g/l	lethal	----	Cl^-
Pb	Crassostrea virginica (oyster)			6131
	0.2 ppm	not toxic	49 days	----
	Crassostrea virginica (Eastern oyster)			6004
	0.5 mg/l	TL_m	12 weeks	Pb^{++}
	0.3 mg/l	TL_m	18 weeks	Pb^{++}
	0.1-0.2 mg/l	noticeable tissue changes	12 weeks	Pb^{++}
	Macrocystis pyrifera (giant kelp)			6000
	4.1 mg/l	no deleterious effects on rate of photosynthesis	4 days	----
	Mya arenaria (soft-shell clam)			6131
	0.2 ppm	apparently not toxic	84 days	----
Hg	Acartia clausi (copepod)			6241
	0.05 mg/l	50% mortality	2.5 hours	Cl^-
	0.05 mg/l	50% mortality	2.3 hours	I^-
	Macrocystis pyrifera (giant kelp)			6000
	0.05 mg/l	50% photosynthesis decrease	4 days	Cl^-
	0.1 mg/l	15% photosynthesis decrease	1 day	Cl^-
	0.1 mg/l	inactivation	4 days	Cl^-
Ni	Macrocystis pyrifera (giant kelp)			6000
	1.31 mg/l	no effect	----	$SO_4^=$
	13.1 mg/l	50% photosynthesis reduction	4 days	$SO_4^=$
Zn	Macrocystis pyrifera (giant kelp)			6000
	1.31 mg/l	no effect	4 days	$SO_4^=$
	10 mg/l	50% "inactivation"	4 days	$SO_4^=$

of acute toxicity information have been made by Doudoroff and Katz (6235) and McKee and Wolf (6000). Ingols (6239), Jones (6291), Sprague (6161, 6155) and Woelke (6232) and others have reviewed factors which relate to the measurement of toxicity.

Acute toxicity has usually been measured as a 24-, 48-, or 96-hour TL_m (median tolerance limit) or roughly equivalent parameter (LD_{50}, etc.). The concept of a threshold concentration refers to a concentration below which the organism could live almost indefinitely (Lloyd and Herbert, 6359). The 96-hour TL_m is an experimentally feasible approximation to the above concept. Because many log-toxicant concentration vs. log-time of measureable response plots are almost parallel to the time axis at 96 hours (see Figure 15-3, also Lloyd and Herbert, 6359), the approximation can be quite good. For points on the left arm of the curve, a small change in some parameter (temperature, another toxin, etc.) may produce relatively large changes in the time to 50% mortality (frequently observed), but small changes in the observed TL_m (see Lloyd, 6267).

It would be well to discuss the concept of "synergism" at this point. There seems to be considerable imprecision in the literature in the use of the word with respect to the effects of environmental pollutants (see Sprague, 6155). Synergism is defined as "cooperative action of discrete agencies such that the total effect is greater than the sum of the two effects taken independently." (Webster's 7th New Collegiate Dictionary, 1967). To clarify what is meant by synergism, then, we must clarify what we mean by the "effect" of the toxicant. There are two "effects" encountered in our normal methodology: (1) shortening of survival time ("time potentiation") at a given concentration of toxicant, and (2) lowering of amounts necessary to kill a certain fraction of the sample in a certain time interval ("threshold lowering"). Both are of concern in considering nearshore pollution. In areas immediately around outfalls, the rates of toxic reaction may be important, particularly to organisms which depend on avoidance reactions for survival. In areas away from outfalls, long-term exposure to slightly elevated levels of "synergistic" toxicants would be important.

Figure 15-3, taken from the paper of Sprague and Ramsay (6260) illustrates the distinction between time potentiation (vertical displacement of the lower part of the curve) and threshold lowering (horizontal curve-displacement). In fact, no study was found in the literature which conclusively demonstrates trace metal-trace metal threshold lowering as opposed to time potentiation.

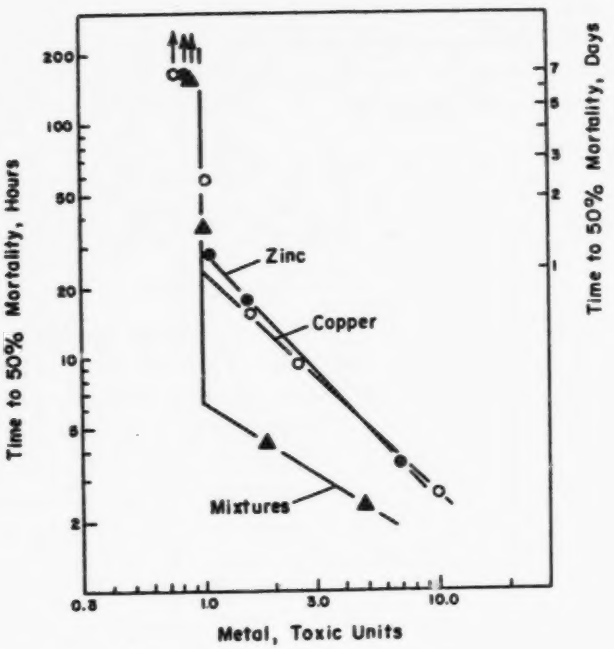

Figure 15-3. Median mortality-time versus concentration of metal expressed in toxic units for young salmon. Toxic units for a metal are fractions or multiples of its incipient lethal level (vertical line). The strength of mixtures is the sum of the toxic units of each component, in this case copper and zinc. (After Sprague, J. B. and B. A. Ramsay, Journal of the Fisheries Research Board of Canada, 1965, with permission.)

Trace metal-temperature "synergism" has been frequently cited as a potential danger attendent to thermal pollution (see review of de Sylva, 6283). However, the recent conclusion of Sprague (6155) that "...no assumptions should be made about temperature effects on toxicity" is well supported by the literature. Certainly, there is often a time potentiation effect (see references given by Sprague, 6155). However, Lloyd (6267) presents data and cites four references to show that trace metal-temperature threshold lowering may not occur. A study by Portmann (6006) seems to suggest otherwise. However, Portmann (personal communication, 6291) agrees that additional evidence is needed to confirm the presence of threshold lowering. In addition, Sprague cites unpublished data to the effect that the incipient lethal level of zinc to salmon is actually lower at lower temperatures (6155).

Effects of sub-lethal levels of some trace metals on growth, respiration, and reproduction of some marine organisms have been studied (Bougis, 6114, 6100; Clendenning and North, 6113, see Table 15-6), but many more studies are needed.

Data obtained from laboratory toxicity tests using individual species should be applied to the prediction of nearshore marine pollution with caution. Estimates of acceptable environmental levels include one-tenth of the 48-hour TL_m (Burdick, 6323) and one-tenth of the 96-hour TL_m (Wurtz, 6233). Beak (6276) had considered a similar estimate to be "little more than an intelligent guess". One-hundredth of the 96-hour TL_m has been recently suggested by the U. S. National Technical Advisory Committee (6004). Sprague (6155) reviews studies on water quality criteria relating to the validity of these assigned levels.

Natural populations: The determination of the short-term tolerance of a population is roughly equivalent to determination of the most sensitive species in the population. Provided the appropriate techniques can be worked out, acute toxicity tests applied to natural populations will be a systematic and relatively rapid method of singling out critical "indicator" species. In addition, such tests inherently take into account organism-organism interactions. Ways in which toxicity may be altered in a natural population are uptake of the toxic substance by less sensitive species (see, for example, Keil and Priester, 6083), and excretion of organic substances which bind or chelate the toxic substance (see Provasoli, 6367).

Studies of sub-lethal effects on natural populations may be prohibitively difficult with our present technology. If, however, we can elucidate some simple interactions in a population, we may be able to piece some meaningful "partial population" experiments together. An example of an experimentally reasonable partial population study has been suggested by Waldichuk (6248). He pointed out that laboratory predator-prey experiments could be expanded to include a study of the effect of pollutants on this important relationship between organisms.

Ecological models: No attempt has been made to list or evaluate ecological models. Their mention here is to indicate the possibility for their use in evaluating pollution problems.

The goals of ecological models are parallel to those of chemical thermodynamics; to be able to describe the state of the system of small "particles" in terms of observable macroparameters. The choice of a "standard" or reference state of a biological system will be difficult. The choice of variables is not obvious. There may not be basic variables for biological systems corresponding to temperature, pressure and volume in gaseous chemical systems.

An example of a measurable parameter which may be usable in modeling biological systems is species diversity, which has been described by a number of statistical indices. It is thought that "stability" of an ecosystem (ability to withstand environmental stress) increases with increased species diversity. This relationship must be further investigated (Pearson, Storrs, and Selleck, 6366).

Summary

1. The physical and chemical forms of trace metals in sea water are important to a consideration of their behavior as potential pollutants.
2. Very little is known about nearshore trace metal concentrations on the open coast of the Pacific Northwest. Inference from other "similar" locales is not justified at the present state of knowledge about factors which control trace metal concentrations.
3. Some of the processes which may remove trace metals from sea water are precipitation, sorption, flocculation and biological uptake. The relative importance of these mechanisms for specific areas is not known.
4. Although there is a fair amount of information on the short-term acute toxicities of trace metals to specific marine organisms from the Pacific Northwest, methodological questions and lack of long-term or sub-lethal studies make it difficult to predict safe levels.

In the course of this study, several individual metals were selected for more intensive study. The metals selected were those with apparently high potential for pollution of nearshore waters of the Pacific Northwest. These metals were mercury, copper, lead, and zinc.

MERCURY

In the late 1950's and early 1960's, organo-mercury compounds on fish and shellfish from Minamata Bay, Japan caused severe neurological disorders in 111 persons and killed 41. There were 19 cases of congenital disorders attributed to the same cause (Irukayama, 6277).

In 1966, Sweden prohibited the use of methyl-mercury as a seed-dressing after significant bird mortalities (Jernelöv, 6220).

In 1970, fish from Lake Erie were found by Canadian researchers to contain mercury levels higher than those allowed by existing health standards (Anon., 6013). The major source of mercury in Lake Erie was from chlorine-caustic soda production plants (Anon., 6298). There are several chlorine-caustic soda plants in the Pacific Northwest, primarily for the purpose of supplying chlorine needed for bleaching pulps, although none yet are situated on the open coast. In addition, the continued use of organo-mercurial fungicides as seed treatment (Anon., 6289), the limited use organo-mercurials in the pulp and paper industry (which has been reduced in recent years), and the presence of economic deposits of mercury-bearing ores in the area (Highsmith, 6340) warrant some consideration.

The quantity of mercury in nearshore waters and in rivers in the Pacific Northwest has never been measured. There are very few determinations of mercury in sea water. The range of observed open oceanic values is from 0.08 to 0.27 μg/l (Hamaguchi, Kuroda, and Hosohara, 6065; Hosohara, 6070). In Minamata Bay in 1960, values for total mercury (oxidized samples) ranged from 1.6 to 3.6 μg/l. Mercury in unoxidized samples was about one-tenth of this value (Hosohara *et al.*, 6071).

Mercury has been detected in marine organisms in the following concentrations: brown algae, 0.03 ppm dry weight; mollusca (tissues), 1 (?) ppm dry weight; pisces, 0.3 (?) ppm dry weight (Bowen, 6019). Question marks are those of the cited reference and indicate questionable values. Haddock and cod caught near Sweden contained 0.044 ppm and 0.031 ppm wet weight respectively (Westöö, 6278).

The behavior of mercury in the natural environment is not well understood. It has been established that inorganic mercury is converted to methyl-mercury in anaerobic sludges (Jensen and Jernelöv, 6242). This may be a chemical transfer reaction, although regeneration of methylcobalamine, one necessary factor for the reaction, is enzymatic (Wood, 6009).

Mercury in most of its chemical forms is adsorbed onto sediments. Some of this adsorbed mercury is very slow to exchange with the water (Hannerz, 6003). Marine sediments taken near the Hyperion outfall at Los Angeles contained up to 50 times more mercury than similar unaffected sediments (up to 1 ppm) (Klein and Goldberg, 6286).

Chemical form is extremely important to the biological behavior of mercury. The species of primary concern in sea water will be $HgCl_4^{=}$, $HgCl_3^{-}$, $HgCl_2$; CH_3HgCl; and $(CH_3)_2Hg$; inorganic mercury, methyl-mercuric chloride, and dimethyl mercury respectively. All are quite soluble in water. Dimethyl mercury[$(CH_3)_2Hg$] is volatile and is changed to methyl-mercuric chloride (CH_3HgCl) under slightly acidic conditions (Wood, Kennedy, and Rosen, 6010).

CH_3HgCl and $(CH_3)_2Hg$ diffuse more easily than the inorganic species through biological membranes(Wood, 6009). Uptake of mercury by organisms is generally more rapid than excretion, which is one factor involved in accumulation (Hannerz, 6003). Thus we might expect organo-mercurials to be more highly concentrated by organisms than inorganic mercury. This is observed (Hannerz, 6003). Westöö (6278) found that 82% of the mercury in Swedish marine fish was CH_3Hg Cl, although it is possible that $(CH_3)_2Hg$ was converted during the analysis procedure.

It should be noted that the concentration of mercury in organisms is not necessarily related to its place in the food chain (trophic level), but to such factors as the uptake-excretion balance (metabolism), and size of individuals. The variations between individual organisms of the same species are very large, with as much as a factor of twenty between the lowest and highest concentrations in a single laboratory sample (Hannerz, 6003).

Organo-mercurials are considerably more toxic than inorganic mercury to marine organisms, particularly vertebrates (Löfroth and Duffy, 6281) due to the more rapid membrane passage. Bond and Nolan (6222) tested 32 mercury compounds, 9 inorganic salts and 23 organo-mercury compounds, on the snail Australorbis glabratus. The most effective inorganic salt ($HgBr_2$) produced 80% mortality in 24 hours at 1 ppm concentration, although it produced no mortalities at 0.5 ppm in the same time interval. Twelve organo-mercury compounds, on the other hand, produced significant mortality at the 0.3 ppm level.

The acute toxicity of mercury to marine organisms is high. Bivalve larvae were killed by 20 µg/l (McKee and Wolf, 6000). Copepods (Acartia clausi) were killed in 2.5 hours by 50 µg/l (Corner and Sparrow, 6241). Bryozoan larvae (Watersipora cucullata) were found to have a 2-hour TL_{50} of 100 µg/l (Wisely and Blick, 6247). These short-term results, combined with the observation of Böetius (cited in McKee and Wolf, 6000) that mercury is "infinitely toxic" if the exposure is long enough, suggest that acute toxicity of mercury may be important.

Giant kelp (Macrocystis pyrifera) suffered a 50% decrease in photosynthetic capacity on exposure for 4 days to 50 µg/l (McKee and Wolf, 6000).

A temperature-mercuric chloride synergism has been reported by Portmann (6006). He showed that LD_{50} (48 hour) for the cockle (Cardium edule) at 5° C was 130 times that at 22° C. The LD_{50} for the brown shrimp (Cragon cragon) changed only by a factor of 5 over the same temperature interval. However, Portmann (personal communication, 6291) has indicated that more study is needed to confirm this apparent synergism.

Summary

1. Mercury has great pollution potential.

2. Mercury concentrations in sea water may be around 0.1 to 0.3 µg/l.

3. The behavior of mercury in the natural environment is not well understood; certain conditions favor the production of methyl-mercury in sediments.

4. Marine organisms concentrate mercury. Methyl-mercury is even more highly concentrated.

5. The acute toxicity of mercury to marine organisms is high.

6. Temperature may have a effect on mercury toxicity.

COPPER

Our concern with copper as a potential pollutant stems from its extensive use in industry and its relatively high toxicity to marine organisms. Pollution with copper has been observed in a number of harbors on Long Island Sound (Prytherch, 6195; Galtsoff, 6056). Sources of copper pollution are copper pickling and plating processes (electronics industry, metals industry), algicides, corrosion of condenser tubing in thermal electric plants (see Roosenburg, 6324; USDI, 6240), marine antifouling paints, and many other industrial processes (see Appendix 4). The addition of copper from corrosion of the condenser tubing in thermal electric power plants may be negligible (USDI, 6254), but may vary considerably depending on the antifouling additives which are used.

There are many measurements of copper in sea water. Only the more recent ones distinguish between inorganic and organic copper. Corcoran and Alexander (6193) and Alexander and Corcoran (6192) working in the Caribbean found less than 2 μg ionic copper/l with less than 1μg/l below 50 m. Particulate copper was less than 0.5 μg/l. Total soluble copper (<0.5μ) was 4-13 μg/l with occasional values as high as 20 μg/l.

Williams (6040) found organically bound copper ranging from 0.0 to 0.45 μg/l, and inorganic copper from 0.38 to 4.26 μg/l in near-shore areas off San Diego. There was no correspondence between amounts of organic and inorganic copper found. The percent organically associated ranged from 0-28% of the total. The nature of the organic association is not known.

Although only ionic copper is toxic to fish, there are indications that complexed copper may be as toxic to algae as ionic copper (Ingols, 6239). Whether the organically associated copper has a nature similar to this "complexed" copper is not known. The possibility needs further investigation, particularly in light of the wide variations in "organic" copper reported above.

The ways in which the nearshore marine environment assimilates copper "pollution" may be very complicated. Divalent copper was strongly and consistently adsorbed on all materials tested by Krauskopf (6102). Chow and Thompson (6037) showed that under certain conditions, shallow sediments release copper to sea water. The concentration of Cu^{++} in equilibrium with $Cu(OH)_2$ in sea water is about 20μg/1 (calculated from solubility constant values presented by Duursma and Sevenhuysen, 6213) at 18-20° C. Yet values up to 600 μg/1 total copper are observed (Prytherch, 6195). Thus the organic involvement of copper in the marine environment seems to "stabilize" relatively large concentrations of copper in solution.

There are more data on the toxicity of copper to marine organisms than on any other metal, probably due to its extensive use in marine antifouling paints. Bougis (6114) showed that 10 to 20 μg Cu/1 slowed the growth of sea urchin pluteaus. 26 μg/1 $CuSO_4$ in the presence of EDTA inhibited growth of the phytoplankton Exuviaella at 30° C (USDI, 6240). A number of other phytoplankton species (Coccochloris elabens, Glenodinum foliaceum, Prorocentrum sp.) have similar tolerance levels (USDI, 6240; Marvin, Lansford, and Wheeler, 6252; Mandelli, 6354). On the other hand, the minnow, Fundulus heteroclitus tolerated 30 mg/1 (30,000 μg/1) for 4 days (Doudoroff and Katz, 6235). Even higher concentrations (up to 18 g/1) were used to kill bacteria (USDI, 6253). High copper concentrations in sea water make oysters unfit for human consumption (Roosenburg, 6324).

Summary

1. Copper is common in many industrial effluents, particularly those of heavy industry.

2. The processes by which the environment deals with copper are complicated by organic involvement.

3. Copper has a high toxicity to marine organisms.

4. Sub-lethal copper pollution can make oysters unfit for human consumption, and may slow growth of other marine organisms.

The ways in which the nearshore marine environment assimilates copper "pollution" may be very complicated. Divalent copper was strongly and consistently adsorbed on all materials tested by Krauskopf (6102). Chow and Thompson (6037) showed that under certain conditions, shallow sediments release copper to sea water. The concentration of Cu^{++} in equilibrium with $Cu(OH)_2$ in sea water is about 20µg/l (calculated from solubility constant values presented by Duursma and Sevenhuysen, 6213) at 18-20° C. Yet values up to 600 µg/l total copper are observed (Prytherch, 6195). Thus the organic involvement of copper in the marine environment seems to "stabilize" relatively large concentrations of copper in solution.

There are more data on the toxicity of copper to marine organisms than on any other metal, probably due to its extensive use in marine antifouling paints. Bougis (6114) showed that 10 to 20 µg Cu/l slowed the growth of sea urchin pluteaus. 26 µg/l $CuSO_4$ in the presence of EDTA inhibited growth of the phytoplankton Exuviaella at 30° C (USDI, 6240). A number of other phytoplankton species (Coccochloris elabens, Glenodinum foliaceum, Prorocentrum sp.) have similar tolerance levels (USDI, 6240; Marvin, Lansford, and Wheeler, 6252; Mandelli, 6354). On the other hand, the minnow, Fundulus heteroclitus tolerated 30 mg/l (30,000 µg/l) for 4 days (Doudoroff and Katz, 6235). Even higher concentrations (up to 18 g/l) were used to kill bacteria (USDI, 6253). High copper concentrations in sea water make oysters unfit for human consumption (Roosenburg, 6324).

Summary

1. Copper is common in many industrial effluents, particularly those of heavy industry.

2. The processes by which the environment deals with copper are complicated by organic involvement.

3. Copper has a high toxicity to marine organisms.

4. Sub-lethal copper pollution can make oysters unfit for human consumption, and may slow growth of other marine organisms.

LEAD

It has been recently estimated that 100,000 tons of lead aerosols are produced annually in the Northern Hemisphere (Murozumi, Chow, and Patterson, 6360), primarily by the burning of fuels containing tetraethyl lead. The effect of this industrial input of lead into the oceans is noticeable in oceanic lead concentrations. The deep sea lead concentration is about 0.03 μ g Pb/l. It has been estimated that surface lead concentrations were similar prior to the industrial revolution (Tatsumoto and Patterson, 6160). Now surface values run fairly consistently between 0.1 μg/l and 0.4 μg/l(Chow, 6031, 6032; Tatsumoto and Patterson, 6160). In localized areas, values may run as high as 1.5 μg/l (Loveridge et al., 6109) or even 5 μg/l (Noddack and Noddack, 6121).

Rivers in the Pacific Northwest have, generally, a high lead content, around 4 μg Pb/l (Durum and Haffty, 6208).

The acute toxicity of lead to marine organisms is poorly known. An 18-week TL_m for the oyster Crassostrea virginica was measured to be 300 μg/l. 100 μg/l was observed to cause noticeable tissue changes in 12 weeks (USDI, 6004). On the other hand, 4 mg/l had no effect on Plaice embryos (Doudoroff and Katz, 6235), and 200 mg/l was required to cause abnormalities in sea urchin eggs (McKee and Wolf, 6000).

Lead is accumulated in marine organisms, although not to the same degree as zinc. Marine plants have been observed to contain 8,400 ppb compared to a sea water concentration of about 0.1 ppb (Bowen, 6019).

Summary

1. Man has significantly changed the lead content of surface sea waters.

2. The lead concentration in coastal waters of the Pacific Northwest in unknown. Rivers in the area have around 4 μg Pb/l.

3. Sub-lethal effects will probably be more important than acute toxicities.

ZINC

In spite of its relatively low acute toxicity, zinc is of concern in our study of coastal pollution. This is primarily due to observed sub-lethal effects. The high concentration factor of zinc in marine organisms (USDI, 6004; McKee and Wolf, 6000) is also of interest.

Observed zinc values in nearshore areas range between 3 (Morris, 6117) and 50 μg/l (Brooks, 6189). Zinc apparently has a fairly strong organic association in sea water, similar to copper (Rona et al., 6137; Barsdate, 6280). The values of Buffo (6175) thought to be affected by contamination (Cutshall, pers. comm.) but could be largely due to upwelling (see Schutz and Turekian, 6141). Buffo (6175) found an average of 22 μg/l in surface samples from off the Oregon coast.

Zinc in rivers of the Pacific Northwest is generally around 10 to 20 μg/l (Kopp and Kroner, 6251; Durum and Haffty, 6208), but values up to 300 μg/l have been observed (Kopp and Kroner, 6251).

Acute toxicities of zinc to marine organisms are generally around 5 to 10 mg Zn/1, although some of these were measured over very short time intervals (Wisely and Blick, 6247). Invertebrate larvae seem to be the most sensitive of the organisms tested (Wisely and Blick, 6247). Growth of the larvae of Poracentrotus lividus (a sea urchin) was retarded by only 30 μg Zn/l (Bougis, 6100). 160 μg Zn/l caused abnormalities in sea urchin eggs (McKee and Wolf, 6000). The division rate of the diatom Nizschia was reduced by exposure to only 0.25 mg/l (Chipman, Rice, and Price, 6224).

Summary

1. Zinc is somewhat variable in nearshore waters, but Oregon coastal values are probably around 20 μg/l.
2. Organic involvement may "stabilize" high zinc concentrations in sea water.
3. Acute toxicities are moderate, but sub-lethal effects may be important.

Chapter 16. RADIOCHEMISTRY

by William C. Renfro

The Pacific Northwest coastal region is one of the unique areas of the world from a radiochemical viewpoint. Any sample of water from this area may contain radioactive elements from several different sources, including the following:

A. naturally-occurring radionuclides,

B. fallout fission products from nuclear weapons tests, and

C. neutron-induced radionuclides from fallout and from the Hanford plutonium production reactors.

To understand the levels of radioactivity in water, sediments, and biota of the region, it is most convenient to discuss the radionuclides on the basis of their origin.

A. Naturally-occurring radionuclides

Radionuclides occurring naturally are essentially of two kinds: long-lived primordial radioisotopes with their decay products and cosmic ray-induced radionuclides.

^{40}K

From the standpoint of background radioactivity levels in sea water, potassium-40 with a half life of 1.26×10^9 years is a most important primordial radionuclide. More than 90% of the total radioactivity in sea water is due to ^{40}K (Burton, 4187) because potassium is a major element in sea water averaging 0.39 g K/l (of which 0.0118% is ^{40}K). Furthermore, potassium constitutes a significant fraction (0.2-0.3%) of the elemental composition of man, fish, and other organisms so that the natural abundance of ^{40}K accounts for a large part of the internal irradiation all organisms experience.

Relatively few measurements of ^{40}K in the Pacific Northwest marine environment have been published, probably because this radionuclide is so ubiquitious as to be of little interest to most investigators. Gross, McManus, and Creager (4218) observed ^{40}K concentrations averaging about 25 picocuries per gram (pCi/g) dry sediment in the area around the mouth of the Columbia River. This value (25 pCi/g) is in general conformance with the ^{40}K sediment levels measured by Toombs and Culter (4217) throughout the lower Columbia River and Tillamook Bay.

The concentration of ^{40}K in sea water is stated by Burton (4187) to be 0.324 pCi/g. Osterberg (4069) measured ^{40}K in euphausiids (small marine crustaceans), lantern fish, shrimp, and viper fish caught along the Oregon coast. With few exceptions ^{40}K activities in these organisms ranged from 0.6 to 1.3 pCi/g wet weight. Seymour and Lewis (4093) reported a range from 2 to 6 pCi/g wet weight in intertidal marine organisms near the Columbia River mouth. Almost all marine and estuarine organisms analyzed by Toombs and Culter (4217) averaged 2 to 3 pCi/g wet weight. It appears from these observations that the concentration of ^{40}K in marine organisms can be expected to be near 2 pCi/g regardless of their habitat.

^{87}Rb

Another radionuclide in sea water contributing a small fraction to the total sea water radioactivity (less than 1% of that due to ^{40}K) is ^{87}Rb with a 4.8×10^{10} year half-life. Since its activity in sea water is only 0.003 pCi/ml (Burton, 4187) and because most marine organisms do not concentrate Rb to high levels (concentration factors from 1 to 26; Polikarpov, 4219), ^{87}Rb is not greatly important as a source of internal radiation.

^{232}Th, ^{235}U, ^{238}U

Of particular interest to oceanographers and geochemists are the naturally-occurring elements having atomic numbers greater than 83 (bismuth). All these elements are radioactive and belong to the decay chains of ^{238}U (4.51×10^9 years), ^{235}U (7.13×10^8 years), or ^{232}Th (1.39×10^{10} years). Under certain conditions, the relative activities of a parent-daughter pair of radionuclides in a decay chain can be used to determine rates of oceanographic or geochemical processes.

The concentration of uranium in well-mixed sea water averages about 3.3 μg/l or 2.2 pCi/l (Burton, 4187) of which 99.3% is ^{238}U and 0.7% is ^{235}U. The amount of thorium in sea water is very low, being on the order of 10^{-9} g/l (Prospero and Koczy, 4011). In sediments uranium may be present in concentrations around 1 microgram per gram (μg/g) but may be concentrated to high levels in certain reducing conditions and when associated with highly organic sediments (Burton, 4187). Thorium in oceanic sediments varies largely with the amount of clay present, ranging from 2-12 μg/g (Prospero and Koczy, 4011). In marine organisms the concentrations of both thorium and uranium are usually hundredths of μg/g wet weight (Bowen, 4220). Despite the generally low concentrations of uranium and thorium parent elements in marine organisms, some daughter radionuclides further down the decay chains may contribute significantly to the total radiation background. For example, ^{222}Rn is a radioactive gas in the ^{238}U decay chain which escapes from sediments, sea water, and land to the atmosphere. In turn, its radioactive daughter, ^{210}Pb, can return to the ocean in precipitation and constitute a significant fraction of the internal radiation background of marine animals (Beasley, 4193).

Other primordial radionuclides

Other primordial radionuclides having very long half lives from 10^7 to 10^{15} years include ^{50}V, ^{115}In, ^{138}La, ^{144}Nd, ^{147}Sm, ^{152}Gd, ^{174}Hf, ^{176}Lu, ^{180}Ta, ^{187}Re, and ^{190}Pt. Most of these have low concentrations in sea water, and many have not been detected. Hence, these radioisotopes are responsible for only a negligible fraction of the total radioactivity in sea water and, excepting vanadium in tunicates, are not presently thought to be biologically important.

Cosmic ray-induced radionuclides

High energy cosmic rays which originate in outer space and are accelerated by interstellar magnetic fields engage in nuclear reactions with elements in the earth's atmosphere. Some of the nuclear reactions involving cosmic rays produce significant amounts of ^{3}H, ^{7}Be, and ^{10}Be as spallation fragments. At the same time the radionuclides ^{3}H (half-life, 12.3 years) and ^{14}C (half-life, 5730 years) are continuously formed and have proved to be valuable indicators of ocean and atmosphere mixing rates.

^{3}H

Tritium, in addition to being continually produced by cosmic ray neutron interaction with nitrogen ($^{14}N + ^{1}n \rightarrow ^{3}H + ^{12}C$) is also produced in large amounts in nuclear weapons tests, reactor fuel element reprocessing, and nuclear reactors. Although the concentration of ^{3}H in sea water averages about 1 pCi/l (Pertsov, 4097), it does not appear to be concentrated highly by marine organisms. Nevertheless, large and continuing injections of ^{3}H into the biosphere, as from fuel reprocessing activities, should be avoided for they increase the radiation background.

^{14}C

Carbon-14 formed in the secondary cosmic ray reaction ($^{14}N + ^{1}n \rightarrow ^{14}C + ^{1}H$) is also produced in nuclear weapons tests. Cosmic ray-produced ^{14}C is oxidized to carbon dioxide and enters the atmosphere-hydrosphere carbon dioxide cycle. Almost 95% of the exchangeable carbon is in the ocean, mostly in an inorganic form (Burton, 4187). Substantial perturbations in the specific activity of ^{14}C (activity of ^{14}C/g total carbon isotopes) have occurred in the past century due to the burning of ^{14}C-poor fossil fuels and in the past two decades from nuclear weapons tests. The concentration of ^{14}C in sea water is around 0.2 pCi/l.

^{32}Si

Silicon-32 with a half-life of 650 years is produced in the atmosphere by cosmic rays, probably in a spallation reaction with argon (Burton, 4187). The concentrations of ^{32}Si in sea water are very low, being 8×10^{-6} pCi/l (specific activity, 2.7 pCi ^{32}Si/kg Si; Burton, 4187).

^{10}Be

Beryllium-10 with a half-life of 2.5 million years is produced by cosmic ray interactions with atmospheric oxygen and nitrogen.

It has been measured at very low concentrations in deep ocean sediments and is unlikely to be of importance in the nearshore coastal zone.

B. Fission product radionuclides from weapons tests

When a neutron reacts with the nucleus of a heavy element such as ^{235}U, the nucleus often splits, producing two fission fragments. In general, these fission products have unequal masses. The light fragment has an atomic mass around 95 and the heavier fragment's mass is around 139, although detectable amounts of fission products are found throughout the mass region 72-166 (Katcoff, 4221). Some of the important fission fragments and their half-lives are listed below:

Nuclide	Half-life	Nuclide	Half-life	Nuclide	Half-life
^{85}Kr	10.27 yrs	^{106}Rh	30 sec	^{140}Ba	12.8 days
^{89}Sr	54 days	^{127m}Te	90 days	^{140}La	40.2 hrs
^{90}Sr	28 yrs	^{127}Te	9.3 hrs	^{141}Ce	32 days
^{90}Y	64.5 hrs	^{129m}Te	33 days	^{143}Pr	13.7 days
^{91}Y	58 days	^{129}Te	72 min	^{144}Ce	290 days
^{95}Zr	63 days	^{131}I	8.05 days	^{144}Pr	17.5 min
^{95}Nb	35 days	^{133}Xe	5.27 days	^{147}Nd	11.3 days
^{103}Ru	41 days	^{135}I	6.68 hrs	^{147}Pm	2.6 yrs
^{106}Ru	1.0 yr	^{137}Cs	26.6 yrs	^{151}Sm	93 yrs

Since these and other fission product radionuclides invariably have an excess of neutrons in their nuclei, they decay by emitting negative beta particles (Glasstone, 4222). In many cases, fission decay chains result from successive beta emissions. For example, the fission decay chain for mass number 140 is as follows:

$$^{140}\text{Xe} \xrightarrow{\text{16 sec}} {}^{140}\text{Cs} \xrightarrow{\text{66 sec}} {}^{140}\text{Ba} \xrightarrow{\text{12.8 days}} {}^{140}\text{La} \xrightarrow{\text{40 hrs}} {}^{140}\text{Ce}.$$

In this manner, a large spectrum of fission fragments and their daughter radionuclides are present following a nuclear fission test in the atmosphere.

From the first nuclear explosion in the summer of 1945 to the first test moratorium in late 1958, the United States, Great Britain, and Russia detonated 250 nuclear devices. The total energy of the fission events amounted to about 90 megatons (million tons of TNT)as shown in Figure 16-1. In addition, 80 megatons of fusion energy resulted from thermonuclear (fission-fusion) weapons tested prior to the 1958 test moratorium (Eisenbud, 4207). In 1960 France began testing nuclear weapons and in late 1961 and 1962 the United States and Russia resumed tests. The fission products yielded by tests in 1961 and 1962 totalled more than that of all previous fission explosions (Figure 16-1). In addition, massive fusion explosion tests were carried out in 1961 and 1962 which added moderate amounts of fission fragments to the biosphere. In 1963, the United States, Great Britain and Russia signed a treaty banning nuclear testing on the ground, under water, or in space. Since that time only France and Mainland China have contributed fission products to the biosphere.

Vaporized fission products and neutron-induced radionuclides are mixed with surface material swept up into the mushroom. This debris reaches only into the lower atmosphere (troposphere) in the case of fission devices. In contrast, radioactive debris from the larger magaton weapons tests (thermonuclear or hydrogen bombs) is thrown higher, much of it being injected into the stratosphere (Mauchline and Templeton, 4126). Because the tropopause forms a barrier to free exchange of material between the troposphere and the stratosphere, the residence time for bomb debris in the stratosphere is long. As a result, fallout of such material may occur for several years after a bomb test and constitute a continuing source of fission fragments to terrestrial and marine environments.

^{90}Sr

In 1966 Polikarpov (4219) stated that the cumulative contamination of the earth's surface would increase to a maximum by about 1970 (in terms of ^{90}Sr and ^{137}Cs) as the result of inputs from the vast reservoir of long-lived radionuclides in the stratosphere. Despite continued atmospheric nuclear tests by France and Mainland China, fallout of long-lived fission fragments has diminished. For example, ground level ^{90}Sr concentrations in air measured by Shleien, Cochran, and Magno (4223) showed continual decline from late 1963 through

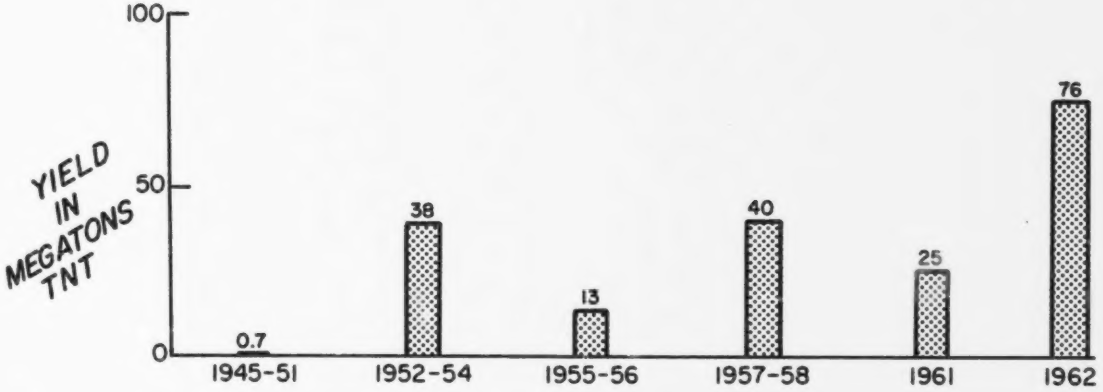

Figure 16-1. Atmospheric nuclear tests prior to the 1963 moratorium. Note that recent tests by China and France are not included (Modified from Comar, 4208).

early 1969. Thus, while the nuclear test ban has resulted in large reduction in fallout of fission fragments, the total levels of long-lived fallout radionuclides is probably near a maximum at present.

The detonation of a nuclear weapon in the atmosphere can rapidly increase the amount of fallout into the oceans. For example, ^{89}Sr and ^{90}Sr produced by the second Chinese test in the Lop Nor area (90°E-40°N) in May 1965 was shown by Kuroda, Miyake, and Nemoto (4224) to travel around the earth in the troposphere in less than one month. Consequently, general statements about concentrations of fission-product radionuclides in the marine environment should be based on long-term averages.

Because ^{89}Sr and ^{90}Sr are not gamma emitters, their measurement is relatively difficult and comparatively few measurements of their concentrations have been made in Pacific Northwest waters. Concentrations of ^{90}Sr in filtered Columbia River Estuary water and in sea water 16 km off the river mouth in July 1964 were reported to be 0.7 ± 10% pCi/l (Park et al., 4077). Reporting on the results of more than 750 analyses for ^{90}Sr in the North Atlantic Ocean surface waters, Bowen et al. (4225) listed mean annual concentrations ranging from 0.08 to 0.20 pCi/l from 1959 through 1967. Although ^{90}Sr is of great concern in the terrestrial environment because of its long half-life, tendency to be incorporated into bone, and dangerous ionizing radiations, it is greatly diluted by the relatively large concentrations of stable Ca and Sr in sea water.

^{95}Zr-^{95}Nb

Fission product ^{95}Zr is a beta and gamma emitter which decays with a 65-day half-life to ^{95}Nb, also a beta and gamma emitter (half-life, 35 days). These radionuclides attain transient equilibrium and are present in sea water almost exclusively in the particulate form. Watson et al. (4004) analyzed estuarine and coastal organisms collected near the Columbia River mouth in April 1959 and in April 1960. They showed that ^{95}Zr-^{95}Nb levels in all plants and animals were declining as the result of decreased world-wide fallout. Furthermore euphausiids (small crustaceans) taken in Oregon offshore waters in the first portion of 1961 gave no evidence of ^{95}Zr-^{95}Nb in their gamma-ray spectra prior to the resumption of Russian nuclear tests in September 1961 (Osterberg, 4069). However, Osterberg (4070) reported ^{95}Zr-^{95}Nb activities as high as 618 pCi/g dry weight in euphausiids taken off Oregon in November 1961. Such rapid changes in levels of fallout fission fragments emphasize the necessity of extended, periodic measurements to establish radioactivity levels in the marine environment.

^{103}Ru and ^{106}Ru

Both ^{103}Ru and ^{106}Ru are important fission products which are associated with particles in sea water. They decay by beta emission to short-lived ^{103}Rh and ^{106}Rh. As with ^{95}Zr-^{95}Nb, ^{103}Ru and ^{106}Ru declined in organisms near the Columbia River mouth from April 1959 to April 1960 (Watson et al., 4004). Similarly, these fallout radionuclides increased by November 1961 to concentrations from 10 to 30 pCi/g dry weight in euphausiids along the Oregon coast (Osterberg, 4070). Seymour and Lewis (4093) also noted great increases in fallout radionuclides in coastal marine organisms as the result of nuclear weapons tests in September 1961.

^{137}Cs

Cesium-137 is a long-lived (half-life, 30 years) fission product which decays by beta emission to ^{137m}Ba (half-life, 2.6 minutes). It remains predominantly in the ionic form in sea water according to Greendale and Ballou (4056). The concentrations of ^{137}Cs in Northeast Pacific Ocean surface waters during late 1959 and 1960 ranged from 0.05 to 0.23 pCi/l (Burton, 4187). Park et al. (4077) reported ^{137}Cs surface concentrations from 0.3 to 0.8 pCi/l in the Columbia River plume off Oregon in July 1964. Despite the fact that ^{137}Cs is a prominent fission fragment in fallout, it is not usually found in high concentrations in marine organisms because of the relatively high levels of potassium, which is chemically similar to and biologically more important than cesium. Polikarpov (4219) stated, for example, that concentration factors of ^{137}Cs (activity of ^{137}Cs per gram organism/activity of ^{137}Cs per gram water) are two to three orders of magnitude higher in freshwater organisms than in marine organisms. Folsom et al. (4215) reported that ^{137}Cs activities in albacore muscle averaged 0.90 pCi/g wet weight, representing a 103-fold concentration over ^{137}Cs concentrations of North Pacific surface waters between January and March 1966.

^{141}Ce

Another fission fragment of interest in the marine environment is Cerium-141, a beta emitter which decays with a half-life of 32.5 days to Praesodymium-141. Cerium is an element which occurs almost entirely in the ionic form in sea water (Greendale and Ballou, 4056). Activities of ^{141}Ce-^{144}Ce in marine organisms near the Columbia River mouth were observed by Watson et al. (4004) to decrease generally between April 1959 and April 1960. Following the nuclear tests of September 1961, Osterberg measured ^{141}Ce activities ranging from 5 to 175 pCi/g dry weight in euphausiids along the Oregon coast. As with ^{137}Cs, freshwater animals have much higher radiocerium concentration factors than do marine animals (Polikarpov, 4219).

C. Neutron-induced radionuclides

In addition to radioactive fission fragments produced by fission and fission-fusion devices, there is an enormous flux of neutrons. These neutrons interact with nonradioactive elements in the air, soil, and bomb structure to form neutron-induced radionuclides. These neutron-induced radionuclides are a conspicuous part of local and worldwide fallout from atmospheric weapons tests.

A second source of neutron-induced radionuclides in marine waters of the Pacific Northwest is the Hanford Atomic Products Operation. This facility, located in Eastern Washington some 650 km up the Columbia River from the ocean, is a site of plutonium production. Plutonium (^{239}Pu) is a fissionable element which serves as the primary ingredient of some fission bombs and as a fuel in nuclear reactors. In the production reactors at Hanford ^{239}Pu is formed in the following reactions:

$$^{238}U + {}^{1}n \quad {}^{239}U \xrightarrow[23\ \mathrm{min}]{\beta} {}^{239}Np \xrightarrow[2.3\ \mathrm{days}]{\beta} {}^{239}Pu$$

To provide the neutrons for plutonium production, large nuclear reactors are necessary and great quantities of heat must be dissipated from the reactor cores. This is accomplished in modern reactors by a closed primary cooling system coupled through a heat exchanger to an external heat sink. However, the eight plutonium production reactors constructed at Hanford between 1943 and 1956 use a "single pass" cooling system in which Columbia River water was pumped through the reactor cores, delayed in cooling ponds, then returned to the river.

In passing through the reactor core various elements, dissolved or suspended in the cooling water stream, are exposed to the great neutron flux and become radioactive. Corrosion of neutron-activated metal parts within the reactor structure also contributes radionuclides to the coolant water. Finally, certain chemicals used to pretreat the coolant water were also made radioactive by neutron activation.

Immediately after its discharge from the reactors the coolant waters may contain up to 200 radioisotopes, the majority very short-lived. Four hours after the water passes through the reactors fewer than 20 radionuclides comprise 99% of the activity (Wooldridge, 4228). During the two to four week passage downriver the concentrations of radionuclides are diminished by physical decay, sedimentation to the river bottom, and accumulation by organisms (Osterberg, 4069). As a result, only a few of the longer-lived radionuclides are readily measurable at the mouth of the river.

Listed below are neutron-induced radionuclides present in fallout and in the Columbia River:

Nuclide	Half-life	Nuclide	Half-life
^{3}H	12.3 years	^{55}Fe	2.6 years
^{14}C	5730 years	^{57}Co	270 days
^{32}P	14.3 days	^{58}Co*	71.3 days
^{35}S	87.9 days	^{59}Fe*	45.6 days
^{46}Sc*	83.9 days	^{60}Co*	5.3 years
^{51}Cr*	27.8 days	^{65}Zn*	245 days
^{54}Mn*	303 days	^{124}Sb	60.4 days

*Gamma-emitting radionuclides occurring in measurable amounts in the river between Hanford and Vancouver, Washington in 1964 (Perkins _et_ _al._, 4226).

The levels of neutron-induced radionuclides introduced into the ocean vary with changes in a number of conditions including the following:

A. number of plutonium production reactors in operation,

B. power levels of the operating reactors,

C. flow rate of the Columbia River,

D. operations of dams and reservoirs between reactors and ocean

E. condition of the fuel element cladding

F. methods of cooling water pretreatment, and

G. concentrations of elements in the water used for cooling.

The numbers of plutonium production reactors at Hanford has decreased in recent years (Figure 16-2). Discounting the N-reactor, which has a closed primary cooling system, the numbers of production reactors in operation has decreased from eight in early 1965 to one in early 1970. This decrease in reactor operations has reduced the levels of neutron-induced radionuclides entering the Pacific Ocean by at least five-fold.

In the nearshore coastal waters of the Pacific Northwest only ^{32}P, ^{51}Cr, ^{54}Mn, and ^{65}Zn have been regularly measured in water, sediments, or marine organisms.

^{32}P

Among these neutron-induced radionuclides only ^{32}P does not emit gamma rays and, for this reason, it is more difficult to measure accurately. Although very small amounts of ^{32}P in marine waters may originate from cosmic ray interactions, essentially all ^{32}P present near the mouth of the Columbia River comes from Hanford. Chakravarti et al. (4050) reported ^{32}P activities from 3.6 ± 0.6 to 8.0 ± 0.6 pCi/l of filtered sea water at stations ranging 16 to 56 km from the Columbia River mouth during July 1963. In June 1966, Isakson (4211) measured the concentration of ^{32}P in filtered sea water at the mouth of the Columbia River at 2.2 pCi/l. This decrease is probably a reflection, in part, of reactor shutdown (Figure 16-2). Isakson (4211) also radioanalyzed various organisms from a single station at the mouth of the Columbia River from September 1965 to September 1966. He observed ^{32}P in clams (*Siliqua patula*) and mussels (*Mytilus californianus*) to increase from February to a peak in April or May with annual averages during the study near 150 pCi/g dry weight.

^{51}Cr

Chromium-51 is the most abundant neutron-induced radionuclide reaching the ocean from Hanford. It is introduced into the Columbia River largely in a dissolved hexavalent anion and, except for small amounts which are reduced to trivalent form and sorbed to particulates, remains in this form at sea (Cutshall, 4229). Because ^{51}Cr remains in the dissolved state and is not appreciably concentrated by marine organisms (Osterberg, Cutshall, and Cronin, 4026), it has been used as a tracer of Columbia River water in the Pacific Ocean. Frederick (4102) used large volume chemical coprecipitation and shipboard gamma-ray analysis to trace the Columbia River plume 380 km south from the mouth in summer and more than 200 km northward in winter during 1966 (see Figure A7-1, Appendix 7). In general, the plume remains offshore from the Oregon coast in summer so that ^{51}Cr concentrations in waters near to shore are low. In the winter, however, the plume is concentrated in Washington coastal waters and has ^{51}Cr activities of 100 pCi/l or more.

Curl, Cutshall, and Osterberg (4030) reported that measurable activities of ^{51}Cr were associated with particulate matter in the Columbia River plume. These authors also showed in laboratory studies that ^{51}Cr in the trivalent oxidation state is actively sorbed to particles in sea water. Although trivalent ^{51}Cr is not to be expected in sea water, since it is not thermodynamically favored (Curl *et al.*, 4030), this radionuclide was measured in sediments as far as 56 km offshore from the Columbia River mouth in August 1962 (Osterberg, Kulm, and Byrne, 4034).

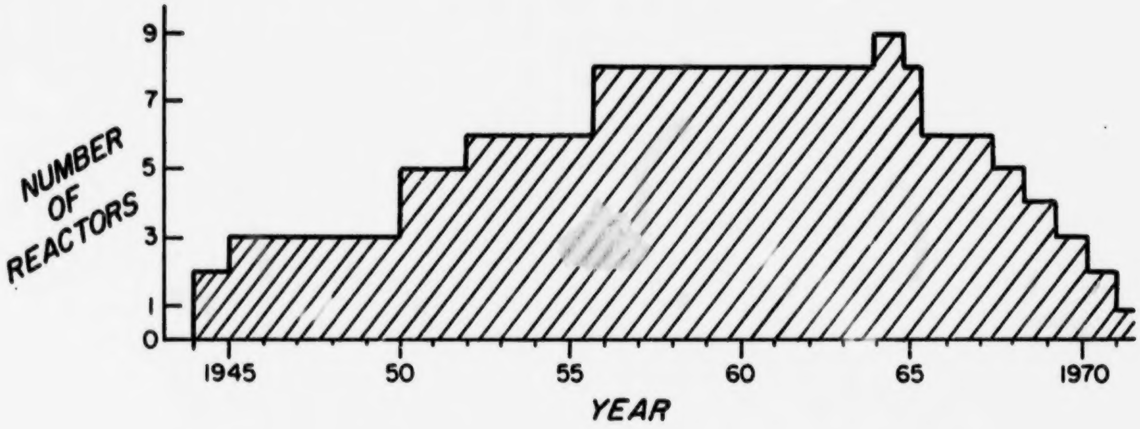

Figure 16-2. Operations of nuclear reactors at the Hanford Atomic Products, Washington. The N-reactor, which became critical in 1964, has a heat exchanger system and, thus, contributes relatively little radioactivity to the Columbia River (Modified from Nakatani, 4204).

The levels of ^{51}Cr in marine organisms are not usually high because chromium has little biological importance. Osterberg, Pearcy, and Curl (4072) observed that ^{51}Cr was not transferred up the food web to higher trophic levels, although it was present in particulate form at a concentration of 16 pCi/l of sea water 24 km off Astoria in April 1962.

^{54}Mn

Manganese-54 is a neutron-induced radionuclide formed in the nuclear reaction: $^{54}Fe + {}^{1}n \rightarrow {}^{54}Mn + {}^{1}p$. This reaction can take place in the fireball of a nuclear explosion or in the reactors at Hanford. The relative contributions of ^{54}Mn to Northeast Pacific Ocean waters from fallout and from Hanford are not well understood. Cutshall (personal communication, 4230) observed during 1963 that the levels of ^{54}Mn in sediments upstream were much lower than sediments downriver from the Hanford reactors. This observation strongly suggests that Hanford contributes significant levels of ^{54}Mn to the Columbia River and plume. In contrast, Kujala, Larsen, and Osterberg (4231) observed gradients in the concentrations of ^{54}Mn in salmon viscera between the Columbia River mouth and Cook Inlet, Alaska in 1964 which suggested that fallout of ^{54}Mn in high latitude Alaskan waters was more important than ^{54}Mn from Hanford. These authors showed that ^{54}Mn in chinook and coho salmon viscera declined 4- to 40-fold between Alaska and Oregon, while ^{65}Zn (predominantly from Hanford) in the same samples had opposite trends. Pearcy and Osterberg (4146), studying ^{65}Zn and ^{54}Mn in albacore between Baja California and Washington during the summers of 1962-1965, concluded that ^{54}Mn enters the ocean from fallout and is more available in offshore waters than in nearshore waters. Folsom et al. (4029) analyzed sea water and biota from Southern California in 1963 and reported a ^{54}Mn average concentration of .059 pCi/l in water and up to .375 pCi/g wet weight of organisms.

^{55}Fe

Iron-55 is produced in the reaction: $^{54}Fe + {}^{1}n \rightarrow {}^{55}Fe$. Most of the ^{55}Fe present in the Northeastern Pacific Ocean probably has originated from the large thermonuclear tests with negligible amounts being contributed by the Hanford reactors (Jennings, 4120).

Although it has a half-life of 2.7 years and is a major radionuclide in fallout from recent nuclear tests, the weak (5.9 kev) x-ray associated with decay of ^{55}Fe is easily absorbed and difficult to measure quantitatively (Palmer and Beasley, 4024). For this reason, it has not been extensively studied. Jennings (4120) reported ^{55}Fe specific activities in the viscera of salmon from Pacific Northwest waters in 1964 ranging from 0.7 to 28.7 μCi/g Fe. Specific activities of ^{55}Fe in sea cucumbers and sediments collected off the coast of Oregon were three to four orders of magnitude lower than those in the salmon (Jennings, 4120).

^{57}Co, ^{58}Co, ^{60}Co

The radionuclides ^{57}Co, ^{58}Co, and ^{60}Co are produced in nuclear tests and are conspicuous in plankton samples in the vicinity of test sites for many weeks after detonation (Lowman, 4149). However, in Pacific Northwest coastal waters only small concentrations of ^{57}Co and ^{60}Co have been reported in plankton (Seymour and Lewis, 4093) and sediments (Gross, McManus, and Creager, 4218; Osterberg, Kulm, and Byrne, 4034). Gross and Nelson (4232) used the ratios of the activities of ^{65}Zn and ^{60}Co to estimate rates of sediment movement along the Oregon and Washington coasts.

^{59}Fe

Iron-59 is produced in the neutron activation reaction: $^{58}Fe + {}^{1}n \rightarrow {}^{59}Fe$ in nuclear reactors and in nuclear explosions. However, the natural abundance of ^{58}Fe is very low (0.3%) so that relatively small amounts of ^{59}Fe are produced. Furthermore, the 45.6 day half-life of ^{59}Fe results in its rapid decay so that it has not been found in measurable amounts in the Pacific Northwest coastal area.

^{65}Zn

Zinc-65 is produced in the reaction: $^{64}Zn + {}^{1}n \rightarrow {}^{65}Zn$ in both nuclear reactors and weapons explosions. This is probably one of the most-studied of all radionuclides for it is biologically important, has a long half-life (245 days), is easily detected, and often occurs in readily measurable amounts in the vicinity of test sites and reactors.

Off the Washington and Oregon coasts ^{65}Zn from the Hanford plutonium production reactors occurs seasonally in all components of the marine ecosystem: water, sediments, and biota. Comprehensive sampling programs sponsored by the U. S. Atomic Energy Commission were initiated in 1961 to learn the distribution and fate of Hanford-produced radionuclides in the vicinity of the Columbia River mouth. Earlier reports by Watson, Davis, and Hanson (4004,4022) established the presence of ^{65}Zn and other radionuclides from fallout and Hanford in estuarine and coastal biota. These authors measured ^{65}Zn in intertidal clams within 20 km north and south of the river mouth ranging from 10 to 147 pCi/g wet weight in 1957, 1959, and 1960.

The distribution of ^{65}Zn in plankton from the offshore areas of Washington and Oregon during the three-year period, 1961-1963, was studied by Lewis and Seymour (4010). Although significant seasonal fluctuations in ^{65}Zn occurred, the levels of ^{65}Zn in unsorted plankton near the river mouth did not change greatly from 1961 to 1963. The geometric mean ^{65}Zn concentrations were highest (200 pCi/g dry plankton) to the north of the river mouth in winter and at the mouth during spring (200 pCi/g) and summer (110 pCi/g). In the autumn the geometric mean concentrations of the Washington and Oregon coastal regions were low (19-41 pCi/g dry plankton).

A number of intertidal animals from the Washington and Oregon coasts have been analyzed for ^{65}Zn. Seymour and Lewis (4093) reported that ^{65}Zn concentrations in mussels (Mytilus californianus) averaged over the period 1961-1963 decreased sharply with increasing distance from the Columbia River mouth. From a mean value of 540 pCi/g dry weight the mussel ^{65}Zn levels diminished to roughly 210 pCi/g at a distance of 80 km north and to about 80 pCi/g at a distance of 80 km south. In January 1966, Mellinger (4128) repeated these coastal ^{65}Zn analyses of mussels along the Washington and Oregon coasts with the following results: mussels at the Columbia River mouth. . . 120 pCi/g, 80 km north. . . 55 pCi/g, and 80 km south. . . 25 pCi/g dry weight. The higher ^{65}Zn levels in mussels from locations north are due to the fact that the winter Columbia River plume is driven inshore along the Washington coast, whereas the summer plume sets to the southwest and tends to remain away from the Oregon coast.

There are abundant reports on ^{65}Zn in pelagic and benthic animals from offshore waters of Washington and Oregon. However, little information is available regarding ^{65}Zn concentrations within 10 km of the coast. Carey (4233) reported that ^{65}Zn specific activities of echinoderms varied with season, depth, distance from the Columbia River, and food habits. Specific activities of ^{65}Zn in echinoderms taken at depths of 200 m or less during June 1966 along the Oregon coast ranged from .02 to .25 pCi/g Zn. In albacore (Thunnus alalunga) livers collected along the Oregon coast in 1963, 1965, and 1966, Pearcy and Osterberg (4146) reported ^{65}Zn specific activities from .02 to .37 pCi/g Zn. In earlier studies Osterberg, Pattullo, and Pearcy (4033) observed that ^{65}Zn concentrations in euphausiids off Newport, Oregon (170 km south of the Columbia River) were sometimes higher than those at the river mouth. They suggested that this condition probably reflected the length of time the euphausiids spent in water containing ^{65}Zn. The ^{65}Zn concentrations in euphausiids taken within 50 km of the shore from July 1961 through August 1962 ranged from 13 to 136 pCi/g dry weight at the Columbia River mouth, 12 to 93 pCi/g at Newport, and 5 to 27 pCi/g at Coos Bay.

Although ^{65}Zn is introduced into the river at Hanford in the cationic form, it becomes increasingly associated with particulate matter during its transit to the ocean (Perkins, Nelson, and Haushild, 4226). Some of the particulate matter in the Columbia River plume settles to the continental shelf and can be identified by its radioactivity. During 1961 Gross, McManus, and Creager (4218) measured ^{65}Zn in the top centimeter of sands along the Washington-Oregon coasts at depths of 60 m or less. The ^{65}Zn concentrations in these samples ranged from 1.3 to 16 pCi/g dry weight. Offshore sediment values reported by these authors ranged from 0 to 460 pCi ^{65}Zn/g with most being less than 10 pCi/g. Osterberg, Kulm, and Byrne (4034) reported that ^{65}Zn concentrations in sediments in and around the Astoria Canyon decreased from about 100 pCi/g dry weight 9 km offshore from the Columbia River mouth to undetectable levels at stations 65 km offshore during August 1962. Recently, the Oceanography Department at Oregon State University has measured ^{65}Zn specific activities ranging from 100 nanocuries per gram zinc (nCi/g Zn) at the Columbia River mouth to 15 nCi/g Zn at the Straits of Juan de Fuca.

^{124}Sb

Antimony-124 is formed in the reaction: $^{123}Sb + ^{1}n \rightarrow ^{124}Sb$ in the nuclear reactors at Hanford. Like ^{51}Cr, ^{124}Sb tends to remain in the ionic state during its passage downriver (Perkins, Nelson, and Haushild, 4226). Both ^{51}Cr and ^{124}Sb appear to be conservative radionuclides, that is, their concentrations are not altered significantly by biological processes but are changed primarily by mixing. For this reason, the ratios of ^{51}Cr-^{124}Sb activities in Columbia River plume waters may hold promise for determining mixing and movement rates. To date ^{124}Sb concentrations have not been reported, although Pope (4205) measured ^{124}Sb in the water at the Columbia River mouth at 1.2 ± 0.2 pCi/l in April 1969.

Future radioactivity levels in coastal waters

Man has little or no control over his exposure to radiations from naturally-occurring radionuclides. Short of moving to another location, a man is generally compelled to accept radiations from the rocks on which he lives and the various building materials about him. However, the levels of artificial radionuclides in the environment from nuclear reactors and weapons tests can be controlled. Thus, man is faced with decisions regarding the environmental costs and the benefits to be derived from the use of nuclear fission and fusion.

Despite the current ban on atmospheric nuclear tests, France and Mainland China continue to explode nuclear devices in the atmosphere. For this reason, the concentrations of fission fragments and neutron-induced radionuclides in fallout can be expected to fluctuate. Until all such tests cease and the reservoirs of radionuclides in the atmosphere stabilize, accurate predictions of fallout radioactivity in surface ocean waters are not possible.

The Limited Nuclear Test Ban Treaty between the United States, United Kingdom, and Russia has contributed to reducing radioactive fallout and to limiting the proliferation of nuclear weapons (Ehrlich, 4234). Furthermore, a provision in this treaty prohibits any underground explosion that causes radioactive debris to be present beyond the boundaries of the country initiating the explosion. This prohibition may place formidable barriers to many peaceful applications of nuclear explosions such as harbor excavations, sea level canal projects, and other nuclear engineering works which might add radioactivity to the biosphere.

An additional source of radioactivity in atmospheric fallout may result from space vehicle incidents. For example, SNAP-9A, an isotope power generator for a space vehicle, burned up in the atmosphere in 1964. This resulted in increased levels of ^{238}Pu (the SNAP-9A power source) in ground level air samples taken in Massachusetts from mid-1966 through 1968 (Schlein, Cochran, and Magno, 4223).

Radioactivity from nuclear reactors is currently of great interest in the Pacific Northwest. The history of reactor operations at Hanford (see Figure 16-2) clearly shows that the number of plutonium production reactors has been drastically reduced. On 29 January 1971 the last plutonium production reactor was shut down. Following this the levels of ^{32}P and ^{51}Cr in the coastal ecosystem should soon become negligible due to their short physical half-lives. However, traces of ^{65}Zn (half-life, 245 days) will remain in coastal sediments and organisms for several years.

According to Wooldridge (4228), an average of 40 Ci of ^{65}Zn was transported past Bonneville Dam each day during 1967. With reductions in the numbers of operating reactors in the following three years (Figure 16-2), the transport rate probably decreased by at least one-half. Hence, if we assume equilibrium between the rate of decay in the ocean and a constant input rate of 20 Ci/day, then about 7,000 Ci of ^{65}Zn should exist in the Pacific Ocean and Columbia River below Bonneville Dam as a result of the Hanford operation. This total inventory in water, sediments, and biota will decay at a rate of 65% per year following shutdown of the last reactor. Thus, in two years (three ^{65}Zn half-lives) less than 15% of the inventory should remain.

At present only three electrical generating stations in the Western United States are powered by nuclear fission. These are: (a) San Onofre in Southern California with an electrical generating capacity of 385 megawatts (MW), (b) Humboldt Bay in Northern California with a capacity of 172 MW (North and Adams, 1531), and (c) the N-reactor on the Columbia River at Hanford, Washington with an 800 MW capacity. These plants employ closed primary cooling loops and thus add minimal amounts of radionuclides to the aquatic environment. Scientists at Hanford are unable to distinguish radioactivity originating in the N-reactor from the higher radionuclide concentrations released to the Columbia River by the plutonium production reactor situated upriver.

Despite the fact that all modern nuclear power reactors are provided with closed loop primary coolant systems in which demineralized water circulates, small amounts of radionuclides do escape to the environment during normal operations. Salo and Leet (4194) stated that radionuclides at the Humboldt Bay plant accumulated from the following: (a) reactor water and steam-system drainage, (b) floor drainage of the radiation zone, (c) liquids associated with fuel handling, (d) fuel storage basins, (3) radiochemical laboratory, (f) laundry, (g) routine maintenance operations, and (h) equipment decontamination operations. At the Humboldt Bay plant these liquid wastes are stored in holdup tanks for decay, filtered, and, if necessary, processed further prior to release to the condenser cooling discharge canal. The principal radionuclides in the discharge waters at Humboldt Bay during 1965 were the neutron activation products ^{65}Zn, ^{54}Mn, ^{59}Fe, ^{51}Cr, ^{60}Co, and the fission fragments ^{134}Cs and ^{137}Cs (Salo and Leet, 4194). The most abundant radionuclide, ^{65}Zn, averaged about 5 pCi/l in the discharge waters during 1965 but was diluted 10^3 to 10^4 times within 30 m of the point at which the effluent entered Humboldt Bay.

Although radioactivity may be expected to be present in exceedingly low concentrations in discharges of a nuclear power reactor, various marine organisms can accumulate and retain some of the biologically important radionuclides for long periods. For example, oysters in the vicinity of the Bradwell nuclear power plant on Blackwater Estuary in England increased steadily in their ^{65}Zn concentration from early 1964 to an apparent equilibrium in early 1967 (Ministry of Agriculture, Fisheries and Food, 4235). Other radionuclides found in low levels around English nuclear power stations include: ^{32}P, ^{55}Fe, ^{60}Co, ^{110m}Ag, ^{134}Cs, ^{137}Cs, and ^{144}Ce (Mitchell, 4236).

To conclude, it seems reasonable to expect that radioactivity in Pacific Northwest coastal waters will continue to diminish in the 1970's. Although natural radioactivity will remain, fallout radionuclide concentrations may decline as the weight of world opinion continues to be exerted on the nations still conducting nuclear weapons tests in the atmosphere. Although nuclear generation of electric power will increase in the Pacific Northwest, radioactivity from nuclear reactors will probably decline as plutonium production at Hanford is phased out.

Despite the possibility that total radioactivity may diminish in the future, research on the distribution and cycling of radionuclides in coastal ecosystems should continue. Such research provides important insight into the fates of radionuclides released to the marine environment by future nuclear power stations. In addition, these studies furnish baseline radioactivity values against which future levels can be compared. It is important, therefore, that detailed studies of radioactivity, community structure, temperature, and other environmental variables be carried on at each plant site before construction and throughout its operational existence.

Summary

1. Coastal waters of the Pacific Northwest contain naturally-occurring radionuclides, fission fragments from nuclear test fallout, neutron-induced radionuclides from nuclear weapons tests, and radionuclides from the plutonium production reactors at Hanford, Washington.

2. Man has no control over the primordial or cosmic ray-produced radionuclides in the ocean. However, these radionuclides occur in very low concentration except for ^{40}K which is present in all sea water, living matter, and sediments.

3. Radioactivity from Hanford has declined due to serial shutdown of the plutonium production reactors.

4. Fallout radioactivity has diminished since the nuclear test ban of 1963. Nevertheless, France and Mainland China continue to create radioactive fallout through atmospheric weapons tests.

5. Research on the cycling of radionuclides now in the marine ecosystem will aid in understanding the environmental impact of future coastal nuclear facilities.

Chapter 17. OTHER POLLUTANTS

PESTICIDES

Introduction

The extensive use of pesticides in agriculture and forestry in the Pacific Northwest warrants a brief consideration of the role of pesticides in nearshore regions of the area. This section summarizes pesticide residue levels which have been observed in the area, the toxicities of various common pesticides to marine species, and the behavior of persistent pesticides in the marine environment.

Pesticide Residues in the Pacific Northwest

Since pesticide levels in natural waters are generally low and quite variable, a bioassay approach is usually taken to determine the extent of pesticide pollution in an area. Since organisms are able to excrete many pesticides only very slowly, the pesticide level in the organisms represents an integrated value over some time interval. Even then, however, there are large variations in pesticide levels from sample to sample and from individual to individual. The cause of these wide variations is unknown.

The Bureau of Commercial Fisheries is conducting an extensive pesticide monitoring program in the United States. Ten or more pesticides were determined in selected organisms. Less than 3% of the samples taken in Washington between 1965 and 1968 were contaminated with pesticides. DDT residues (DDT + DDE), by far the most commonly detected pesticides, were always less than 50 ppb (Butler, 6273). Oysters, Crassostrea gigas, taken in Humboldt Bay, California in 1966-1967 also showed DDT residues to be less than 50 ppb. However, the ova of a king salmon taken in the American River, California in January of 1968 contained 668 ppb total DDT residues (Modin, 6272).

Kraybill (6063) cites observations made in the Willapa Bay area in Washington which show the effects of aerial spraying of forests with DDT on DDT concentrations in oysters (Crassostrea gigas). When the spraying was halted, DDT plus DDE values for shellfish dropped to as low as 0.008 ppm, the lowest value recorded in the United States at that time.

Kraybill (6063) also reported less than 0.1 ppm each of o-p DDT and p-p DDT in oysters from Sheldon, Washington and in shrimp from Bodega Bay, California. Less than 0.02 ppm each of Heptachlor Epoxide, DDE, and Dieldrin were found in oysters from Sheldon and shrimp from Bodega Bay.

Stout (6069) measured concentrations of DDT and its metabolites, DDE and TDE in anchovy (*Engraulis mordax*), Dungeness crab (*Cancer magister*), English sole (*Parophrys vetulus*), hake (*Merluccius productus*), ocean perch (*Sebastodes alutus*), starry flounder (*Platichthys stellatus*), true cod (*Gadus macrocephalus*), and yellowtail rockfish (*Sebastodes flavidus*) taken in Oregon and Washington coastal waters. Concentrations were generally low, less than 100 ppb. Significantly more residue was found in yellowtail rockfish caught near the mouth of the Columbia River than in those caught in Hecate Strait, British Columbia which is near no major river. It was concluded that this was due to agricultural runoff from Oregon and Washington.

Risebrough *et al.* (6271) found from 0.2 to 2.8 ppm total DDT residues in northern anchovy, *Engraulis mordax*, English sole, *Parophrys vetulus*, Pacific jack mackerel, *Trachurus symmetricus*, and hake, *Merluccius productus* caught south of San Francisco. These values may be more representative of the southern California coast than of our area.

More recently, residues in mackerel have been monitored by the Department of Public Health, State of California. Between November 1969, and 11 May 1970, 31 lots of mackerel gave DDT residues ranging from 0.50 ppm to 6.0 ppm. Only 2 of the 31 lots contained more than 3 ppm (Buell, 6270).

The recent review by Edwards (6084) covers pesticide residues on a nationwide scale.

Toxicities of Pesticides to Marine Organisms

An incomplete, but representative, listing of the toxicities of commonly used pesticides to marine organisms is given in Appendix 5.

In general, "... organochloride insecticides are more toxic to marine fauna than other agricultural, industrial, and domestic wastes--including organophosphorous insecticides, soaps and detergents, aziridinyl insect sterilants, slimicides, heavy metals and crude and refined oils" (Eisler, 6048).

Specifically, for phytoplankton, Ukeles (6101) found substituted ureas to be most toxic, closely followed by Lignasan, an organo-mercurial. Chlorinated hydrocarbons, carbamates, and organophosphates complete the list, with considerable differences observed between the toxicities of the various chlorinated hydrocarbon pesticides tested.

For crustaceans, Eisler (6048) found organochlorine pesticides to be generally more toxic than organophosphates, but there was considerable overlap between the less toxic organochlorine compounds and the more toxic organophosphates.

For fish, Johnson (6072) gives a general order of organochlorine, organophosphate, herbicide. He also notes that eggs and larvae are generally more resistant than adults.

The specificity of certain pesticides toward certain kinds of marine organisms may make them useful in marine aquiculture, but it is of more interest in this study to discover which marine organisms will be most affected by pesticide pollution. The specificity of organophosphates will not be considered since they are quite unstable in the environment. Organochlorines will be our biggest concern. Lindane and DDT have both been shown to be toxic to arthropods (copepods) at concentrations which did not harm phytoplankton cultures (Ukeles, 6101).

In addition to the reductions in photosynthesis caused by sub-lethal concentrations of pesticides cited in Appendix 5, sub-lethal concentrations increase the "body burden" of pesticides in organisms. This can affect carcinogenesis, resistance to disease and stress, reproduction, genetic factors, longevity, and vigor in organisms. There may be other factors as of yet unrecognized (Johnson, 6072).

A particularly pertinent example of the effects of sub-lethal exposure is in the results of Ogilvie and Anderson (6274) who suggested that "...DDT may interfere with the normal thermal acclimation mechanism" on the basis of observed changes in the "selected temperature" of Atlantic Salmon.

Behavior of Chlorinated Hydrocarbon Pesticides in the Marine Environment

Although DDT and other chlorinated hydrocarbon pesticides have served mankind quite well, it has become increasingly evident in recent years that their persistence in the environment precludes adequate control and prediction of effects on non-target organisms. As a result, the U. S. Department of Agriculture has announced plans to phase out the use of DDT by 1971 (Anon., 6294). Use in other parts of the world will probably continue for some time.

Although our understanding of the behavior of DDT (and other chlorinated hydrocarbons) in the environment is better than for other compounds, it is still rudimentary. These points have emerged as the relevant factors:

1. DDT is strongly hydrophobic, and has a very low solubility in water. As a result, it is concentrated at sediment-water, and atmosphere-water interfaces (Seba and Corcoran, 6046; Keith and Hunt, 6292). In addition, its high solubility in lipid-containing biological materials produces high biological concentration factors relative to the bulk water mass (Wurster, 6295; Keil and Priester, 6083).
2. The toxic action of DDT is not highly specific, affecting most organisms (Wurster, 6295).
3. DDT is quite stable in the aquatic environment. The exact residence time is difficult to determine (Wurster, 6295; Peterle, 6296).
4. Almost no area of the earth's surface is free from the influence of chlorinated hydrocarbon pesticides, probably as a result of significant atmospheric transport (Frost, 6297; Risebrough *et al*, 6271).

It has been suggested that DDT in the world ecosystem is in steady state. That is, in the 25 years of its use, reservoirs of DDT have been built up into which the rate of input (usage today) is equal to the rate of output (breakdown into non-toxic substances and loss to sediments and other sinks) (Spencer, 6293). It appears, however, that the data on the size of the reservoirs and on the rates of output are at present insufficient to establish the existence of a steady state condition.

Summary

1. Pesticide residue levels in marine organisms in the Pacific Northwest are generally low.

2. Acute toxicities of pesticides to marine organisms are probably less of a concern than sub-lethal effects. Residues may be important to higher predators such as sea birds and man.

3. Although the behavior of DDT in the marine environment is poorly understood, its hydrophobic nature, non-specific toxicity, stability, and modes of transport make it a matter of real concern.

4. Much more information is needed on the overall behavior and effects of DDT in the marine environment.

CHLORINE

Elemental chlorine, Cl_2, does not occur naturally in sea water. Concern with its effects stems from its use as an antifouling agent in thermal electric power plants. Use of chlorine (or substances which hydrolyze releasing Cl_2) varies widely. Use of various methods of preventing fouling are shown below. a response to a questionnaire sent to 69 operating power plants in 1968 (USDI, 6254).

40	Chlorination
1	Chlorination 0.6 ppm at condenser outlet
3	Chlorination, periodic shot feed
3	Intermittent chlorination
9	Sodium hypochlorite
2	Sodium hypochlorite, 3 lbs per min for 20 min for each unit twice a day
1	Sodium hypochlorite, 1.4 lbs per min for 20 min for each unit twice a day
3	Sodium hypochlorite shot fed daily
0	Polyphosphate addition
8	Ferrous sulphate
1	Sodium hydroxide (for pH control)
2	Thermal shock (to inhibit marine growth)
3	None
3	Chlorination, stable residual 7-10 ppm as available Cl_2
2	Chlorination as required to control slime
2	Sodium hypochlorite, 30 min per day

Although intermittent chlorination is apparently the usual practice for operating thermal power plants (USDI, 6254; Hamilton _et al._, 6322) it has been pointed out that continuous chlorination at low levels is necessary to prevent mussels from setting and growing on the effluent pipe (Beauchamp, 6326; Holmes, 6355).

Chlorine in water hydrolyzes rapidly to form HOCL which is the primary toxic principal. HOCL oxidizes organic matter rapidly, and so it, too, is short lived in the marine environment. The major effect of chlorination, then, will be on the planktonic organisms actually transported through the cooling system of the power plant. The total amount of water passing through a 1000 Mw plant in a year would fill an area 60 km by 1 km, 30 meters deep. The existing tidewater power plants in the state of California pass a volume of water 1000 km by 1 km by 30 meters each year (calculated using power generation data of Adams, 6364). In short, a very large volume of planktonic organisms may be subjected to short-term exposures of peak chlorine concentrations.

The effects of such short-term exposures are poorly known. Waugh (6268) showed that nauplii of the barnacle *Elminius modestus* suffered heavy mortalities following a 10-minute exposure to 0.5 ppm chlorine. Larvae of the oyster *Ostrea edulis*, on the other hand, were apparently unharmed by up to 48 minutes exposure to 10 ppm chlorine at 10 C° over ambient temperature.

Chlorination to level of 2.5 ppm (my calculation) was found to decrease primary productivity of effluent waters by as much as 91%. A consistent effect on estuarine receiving waters was not detected, although the calculated maximum effect for the estuary studied was 6.6% (Hamilton *et al.*, 6322).

Summary

1. Chlorine is used as an antifouling agent in many thermal electric power plants.

2. The response of marine organisms to short-term, low level doses of chlorine is highly variable.

3. Phytoplankton are apparently very sensitive to the action of chlorine.

4. Effects on receiving waters are unknown.

PART III - BIOLOGICAL ASPECTS

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Chapter 18. INTRODUCTION TO BIOLOGICAL ASPECTS

by James E. McCauley and Danil R. Hancock

The physical and chemical properties of the coastal zone are important to man because they affect him either directly, or through some of the organisms of the region. The biology of this outer zone becomes important because man depends on many species for food, raw materials, and recreation, but more importantly because he is firmly enmeshed in the complete ecological system which includes marine as well as fresh-water and terrestrial species. The coastal zone, considered by some to be the most productive region of the world (Ryther, 5852), produces 95% of the organic matter in the sea. It is a heavily fished zone where many species feed and where primary productivity is at its greatest. It is important not only because it provides for man but because it is readily accessible and seemingly inexhaustible.

Recent awareness of how man may damage this rich region by using it for a dump has reemphasized the need to study nearshore coastal zones. What will be the effects of dumping large amounts of solid, liquid, and thermal wastes into the coastal zone? Can the biota survive under such conditions? Can man continue to pollute? Do we really know what is there? Much has been written about the coastal zone biology, most of it restricted to the intertidal zone or to commercially important species. This section summarizes biological information as it applies to the nearshore region of the Pacific Northwest. We have arbitrarily dealt with the outer coastal zone from Cape Flattery at the northwest corner of Washington to Cape Mendocino about 180 km south of the Oregon-California border in California. This is a relatively straight coastline with sandy beaches alternating with rocky headlands and with a biota that does not differ greatly from place to place when similar areas are compared. The estuaries and bays represent a special type of habitat; one that is critical to many species of animals as breeding or nursery ground. These areas are highly susceptible to damage from pollution and with few exceptions should be rigorously protected from man's industrial activities. For these reasons we have excluded the bays and estuaries from our studies except in those cases where they were inseparable from the outer coastal zone; e. g. , where a species that occurred in the outer zone spends part of its life in an estuary or where research on the coastal species had been done on an estuarine population.

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Where feasible we have reviewed the information only of those species occurring within 10 km of shore. This is the region where man's impact will be most severely felt; the zone where pollutants are most likely to enter and be diluted. Our goal was to determine the kinds of organisms that occur in this area and to determine their vital requirements, preferences, and limitations. Special emphasis has been placed on the influence of temperature on the species; including special thermal tolerance studies, and the casual notations included in ecological or distributional studies.

The effects of temperature on aquatic organisms has been the subject of a number of comprehensive reviews (Brett, 2796, 2770; Gunter, 2849; Wurtz and Renn, 2565; Naylor, 2798; Warinner and Brehmer, 2690; Kinne, 2378, 2379; de Sylva, 6283; Hedgpeth and Gonor, 3856; and Parker and Krenkel, 3222. In addition, a number of extensive bibliographies have been produced (Trembley, 2692; Kennedy and Milursky, 2926; American Society of Civil Engineers, 3673; Raney and Menzel, 2946). Most of these reviews and bibliographies concern fresh water aquatic organisms and only a few deal with marine or estuarine species. None is specific to the Pacific Northwest coast and none emphasizes the outer coastal region. Naylor (2798) and Kinne (2378, 2379) have dealt primarily with marine and estuarine species but have emphasized European, primarily estuarine species.

The volume of information covered in these reviews and bibliographies is simply overwhelming. Krenkel and Parker (3222) assessed the situation: "Unfortunately the sheer mass of detailed information in these reviews leaves the reader with a feeling of hopeless frustration."

We have concentrated on a limited geographical region with a concerted team effort, attempting to assemble all the known information about species occurring here. To accomplish this study a detailed annotated checklist has been assembled and is included (Appendix 8). Not all groups have been included although some omitted may be extremely important. The marine bacteria, marine fungi, Kinorhynch, and Ostracods have been intentionally omitted. Representatives of the first two groups are often cosmopolitan and the literature is widely scattered. Few of the papers on these groups deal specifically with the Pacific Northwest. Only a single Kinorhynch was found to be reported from the area. The Ostracods were excluded because a detailed review is forthcoming from the University of Minnesota (Swain, in press), and it did not seem necessary to duplicate part of this work.

From the annotated checklist a few species were selected for intensive study. In general, these were the better known species, those commercially or numerically important or subject to intensive biological study.

The biological information available for the coastal zone of the Pacific Northwest is indeed diverse, and the sources are many. Much of the information has been derived from the published literature, but some has come from less readily available sources: progress reports, personal communications, in-house working papers, student reports, etc. Not all the published information is readily accessible, occurring in obscure and unexpected places.

The number of entries in our bibliography indicates the large amount of information that is known, how scattered it is, and why it was necessary to compile it in a review study. Very little of the information can be used directly to assess the impact of an ocean outfall on the environment. Many of the studies which would have seemingly been useful were directed at estuarine or oceanic species instead of coastal species. Still other studies of coastal species have dealt with problems of resource management and have emphasized the effectiveness of legal restraints or artificial propagation. Basic biological studies have often been left to the academic sector, which has contributed significantly to overall understanding of biology but may fail to answer specific practical questions because these questions were not the goals of the study.

We have attempted to assemble all the available biological literature.

Taxonomic Studies

By far, the largest body of information available on the organisms of the outer coast of this region is taxonomic. Our bibliographic citations reflect this situation, even after the omission of some of the very early works which have been subsequently summarized. Many of the citations contain taxonomic or distributional information, describing species, listing the occurrence of a species, or a general group of biota. Some of these listings include very detailed collection locations, others simply infer the presence of a species. These works contain a wide variety of literary styles and therefore are quite erratic in supplying pertinent supplemental information on the requirements, preferences and tolerances of the organisms from this zone. Such variety makes categorizations difficult. For many of the species which do not have direct commercial value the only information known is its collection record(s); i.e., where it has been found. Few of the groups have been monographed for large enough geographic regions to be complete and therefore the amount of additional work required for a coastal site will vary with the location.

The fauna and flora of the nearshore region is known mostly from extensions of studies of intertidal areas, pelagic offshore fisheries studies, or nearshore coastal studies performed in California. Oceanographers are just becoming aware of the urgency for data from this region and hopefully will endure the hardships required to study this inhospitable zone. Generally the adult stages of the macrofauna of the coastal zone from our region will not present serious taxonomic difficulties to qualified personnel studying the region, but larval and juvenile stages, even for the commercial species are not well known taxonomically. Likewise, many of the less popular smaller groups are not well known taxonomically. These include such things as bacteria, fungi, protozoa, phytoplankton, annelids, insects, certain of the crustaceans, and many others which may be extremely important to the community. These groups generally require specialists for identifications and may present real problems to those responsible for siting outfalls on the coast of the Pacific Northwest.

Obviously, the familiarity of the fauna and flora is a function of the number of studies and the kinds of studies previously made. Further, these studies seem to be related to areas near marine biological stations.

Bibliographies

Bibliographies are a time-saving tool to the scientist facing a new problem. If kept up to date, good bibliographies can give a gross indication of the state of knowledge of a subject. Both the number of entries and titles of citations however can be misleading.

Several bibliographies occur for the Cape Flattery to Cape Mendocino region, none of which is directed at the nearshore region. Some of these are regional in nature; others concern an individual organism or a group, while still others concern a general topic such as "Effects of heated effluents on marine organisms," e.g., of which only a fraction is relevant to our region.

Many of the bibliographies concern bays in our region but have some information pertinent to the outer coast. Bibliographies of some value to our review were:

Bryan, (3851), A partial bibliography on Humboldt Bay; Ditsworth (3833, 3854), Environmental factors in Coastal Waters; Pearce, (3852), A bibliography on Marine Benthic Investigations; Butler, (3611), A bibliography on the Dungeness Crab; and the University of Washington's Literature Surveys on Grays Harbor, Coos Bay, and Humboldt Bay (2569, 2568, 2008).

The assessment and prediction of pollution in the nearshore coastal zone as well as determination of indications of normal or "baseline" conditions are dependent on detailed, statistically valid ecological studies. Such comprehensive studies of the nearshore coastal zone of the region encompassed by this study are conspicuously lacking. Our review indicates that only in the southernmost region has this type of study been even attempted. This study was Allen's (2686) work entitled "An oceanographic study between the points of Trinidad Head and the Eel River."

Many pieces of important ecological data are contained in small-scale ecological studies, rather than broad comprehensive investigations. These data have been listed as annotations to the species checklist of Appendix 8. The problem with this data is that it lacks continuity, usually is without time sequence, and is usually directed at different goals.

Chapter 19 deals with the thermal ecology of coastal species of the Pacific Northwest, summarizing the information that is available. It also includes the available information on other physical factors such as salinity, oxygen, and pH. While Chapter 19 deals in general terms, Chapter 20 singles out those species which we consider to be important and which have received the most attention. This Chapter summarizes the data which are available. Not only are ecological data included but other biological data potentially important to pollution studies are included as well.

Chapter 19. THERMAL ECOLOGY OF NORTHWEST SPECIES

by Danil R. Hancock and James E. McCauley

Of concern to many, especially to those involved in the siting of marine coastal outfalls, are the physiological responses of organisms to environmental stresses such as increased temperature, rapid fluctuations in temperature, oxygen, and salinity. Recently, concern has also included the actual environmental conditions dictated by the physiological requirements of the organism i. e., the fact that some organisms actually require fluctuations in temperature (Kinne, 2379; Hedgpeth and Gonor, 3856).

Temperature

Interest in the effects of temperature on marine organisms is not new and perhaps began early in the eighteen hundreds. As early as 1899, H. M. Vernon published a paper entitled "The Death Temperature of Certain Marine Organisms" (2912). Earlier works by Vernon included heat rigor and effects of temperature on respiration (3307, 3306). Recent years have seen a proliferation of information on the response of both freshwater and marine organisms to increased temperatures. The listing of previous general reviews and comprehensive tables covering the extremes of temperatures which can be endured by fishes has recently been done by Parker and Krenkle (3222). The literature describing responses of aquatic invertebrates to thermal gradients by taxonomic groups has been discussed by Jensen et al. (3855). Such reviews generally place major emphasis on freshwater organisms. Although both of these reviews have some information applicable to marine forms, the detailed reviews of Naylor (2798) and Kinne (2379, 2378) are probably the best source for marine and brackish forms. Hedgpeth and Gonor (3856) have presented a brief review of the literature on the marine benthos, particularly as it relates to research needs of the marine benthos.

The review by Jensen et al. (3855) states: "It should be observed: the data used to predict the effects of heated effluents on the biota, the focus of this paper, have rarely been drawn from field studies deliberately designed for these purposes." Our study is in full agreement with this statement, but not, however, with their attempts to formulate general principles and generalizations based on such heterogeneous information. We feel that such broad conclusions must be subjected to further verification, least we succumb to what Chamberlin (3858) refers to as the "Ruling Theory." Most of these studies involve work done in regions of the world other than the Pacific Northwest. The study of Hedgpeth and Gonor (3856), however, includes some data from the central Oregon Coast.

Our attempts to summarize temperature and other physical information by species is presented in Tables 19-1, 19-2, and 19-3. No requirements for admission to this listing were set, therefore information came from a wide variety of sources and may refer to an estuarine form, to an outer coastal form, to an Atlantic population of a Northwest form or to a laboratory study. Jensen et al. (3855) in their review of the role of temperature in the aquatic ecosystem suggest that laboratory results are often based upon the use of laboratory aquaria in which the water quality is less than typical of that found in natural environments. In most laboratory studies they found that aquaria water was either abnormally pure or polluted with toxic nitrogen wastes, or that parasitism was often high due to the stress of overcrowding, or high ammonia levels etc. "In addition, placing animals in heated water cannot simulate natural conditions where heat decays and where animals are free to move to cooler layers." Maximum tolerable temperature may be a poor predictive tool for scientists concerned with the problems of thermal discharges (Jensen et al., 3855). Maximum thermal tolerance depends on water quality, age, condition and size of the experimental animal, reproductive state, previous thermal history, and/or the rate of change of temperature. Thus, the precision of maximum thermal tolerance evaluations necessitate careful delineation of variables by the researchers. For example, temperature limits on the "O" strain of Macrocystis from Baja, California are quite different from those of other regions. We therefore urge that caution be employed when relating specific values from one region to another or from field to laboratory.

Since the data in our tables came from widely scattered studies in which no common denominator of life stage, age size, or previous temperature history was recorded, we have attempted to include these "Classic" papers along with the meager information from the Pacific Northwest and abstract from them published temperature. We do not attest to the quality of this previous temperature information, but present it only to indicate what is available to fulfill the needs of other investigators. Detailed summaries of this information for selected species are presented in Chapter 20.

For the most part, the discussion restricts itself to the particular kinds of temperature information found as compared to what is necessary to make the kinds of decisions currently in demand. Interspersed with the kinds of information available are critical remarks about the quality of this information. We hope that such criticism is both justified and helpful in the design of future research.

Tables 19-1, 19-2, and 19-3 summarize most of the temperature information located in this review. The 129 species, at first glance, may seem quite numerous, yet, when viewed in terms of the 3,000-odd species recorded from this coast it represents only a fraction of a percent.

Table 19-1

Summary of Physical Data on Phytoplankton and Algae

Name	Temperature	pH	See Sources
Phytoplankton			
Phytoplankton (gen.inform.)	10.5-14° C(E)		(7032), (7030), (3527), (7015), (7006), (7008), (7009)
Ampidinium cortesi	18-33° C (R)		(7009)
Asterionells japonica	< 30° C (L), 20-25° C(O)		
Chaetoceros curuisetus	G. R. 17-18° C (E)		(7012)
Chaetoceros gracilis	11-41° C (R), 23-37° C(O)		
Chaetoceros lacinisosus	G. R. 17-18° C(E)		(7012)
Dunaliella tertiolecta	11-36^{+}° C (R) 39° C (L)		(7009)
Eucampia zoodiacus	G. R. 17-18° C(E)		(7012)
Isochrysio gabana			
Monochrysis lutheri	8-< 30° C(R) 14-25° C(O) 20-35° C(L)		(7016), (7009)
Nitzochia closterium	8-< 27° C(R), G. R. 18-20° C(E)		
Procentrum micans	5-30° C (R)		(7037)
Phaeodactylum tricornatum	9-25° C (R)		
Rhizosolenia setigera	5-25° C (R), G. R. 5-20° C(E)		(7016)
Skeletonema costatum	5-30° C (R), 37-40° C (L)	+	(2949)
Skeletonema tropicum	G. R. < 13-31° C(E)		(2469)
Thalaniosera noudenskioldii	< 2-19° C (R)		(7009), (7012)
Dinoflagellates (gen. inform.)	14.2-39° C, -1.39-12.22° C		(7026), (7029)
Macroalgae			
Bossea		+	(2949)
Chlamydomonus reinhardi	6-28° C, 18-28° C(O)		

Table 19-1 (cont'd)

Corallina		+	(2949)
Enteromorpha		+	(2949)
Fucus		+	(2949)
Macrocystis	15-17° C(E), 18-20° C(L)		(5816) (5809)
Nereocystis luetkeana	16-18° C (E)		
Pelvetia		+	(2949)
Ulva		+	(2949)

Key:
R = Range
L = Lethal
E = Experimental
O = Optimum
G. R. = Growth Rate
+ = Data Available

Of those organisms listed in the tables "Temperature Range" information seems to be the most common entry. If all of these data were taken in the same manner or if it referred to a single ecological factor, these so-called ranges would become both meaningful and useful. Such is not the case, and therefore, each datum entered must be considered separately and becomes limited to a specific intended use. The temperature ranges in the literature indicate almost anything. They can mean the two extreme temperatures under which a particular experiment or observation was made, the end points of a temperature curve, the actual range determination made by multiple experimentation, the upper lethal and the lowest temperature at which an experiment was conducted, or any combination of these. Some reports such as Farmanfarmaian and Giese (2835) and Reed (3092) were very explicit and all necessary details were included. Such studies are most valuable.

The temperature at which an organism dies may have little significance if it is far from the natural temperatures the organism might experience. As previously mentioned, itis well established that these limits or tolerance levels are quite dependent on many factors, such as previous temperature history. Tropical species may be living nearer their upper temperature limit and Arctic species may be living near their lower limit. Many of the laboratory studies which have determined temperature requirements for an organism do not use temperature values which would be similar to an organisms natural experience. A major criticism of the values listed in Table 19-1, -2, -3 is that most were presented without the important necessary background information.

In view of the heterogeneity of the information listed under the column "Range" it is perhaps a misnomer to have a column entitled "Miscellaneous," yet information listed is sometimes more specifically categorized as to whether or not it was a rearing range, a temperature at which the organism was observed to live, its eggs hatched, or was spawned.

The optimum ranges of some of the organisms in this study have been determined. These are somewhat obscured by the fact that for at least some of the species the best (optimum) temperatures for reproduction, for survival, or for growth of the various life stages may not be identical. By and large, however, this temperature information is probably the most usable of any temperature data that we encountered.

Information on temperature requirements of larval and juvenile stages is scant. Studies of laboratory rearing of species seem to account for most of the knowledge we have about these sensitive stages of an animal's life. Serious attempts at *in situ* rearing of larvae are absent and published studies of temperature requirements are noticeably lacking for all but a few species.

Although adequate temperature information for no species is completely known, temperature information was found to be nearly adequate for several species. In general, this information was of applied value to the species involved. The species included in Chapter 20 are the best studied and many need only specific goal-related temperature measurements to be useful.

Of the many marine phytoplankton occurring in this region, only the ubiquitous *Skeletonema costatum* is well studied. The temperature range and growth range are known for *Chaetoceros gracilis* and the growth ranges of two other members of the genus, *C. lanciniosus* and *C. curvisetus*, are reported. Similar information was not found for a very important member of this genus *C. armatum*, which is thought to be the major food source of *Siliqua patula*, the Pacific razor clam (personal communication, H. Tegelberg and D. Magoon).

Only a single member of the marine macroalgae is well known thermally. The commercially important *Macrocystis pyrifera* has been studied extensively off Southern California. It occurs in the Pacific Northwest but is less abundant. *Macrocystis integrifolia* tends to replace it in the Pacific Northwest. Studies of temperature, light requirements, effects of turbidity, nutrients, effects of predation, and *in situ* growth rates have been attempted. Much of the data is scattered in progress reports and agency reports. The Final Report of the California Water Resources Agency "The effects of discharged wastes on Kelp" (2994) contains a good deal of information on *M. pyrifera* and its ecological associates.

Little temperature information is known for most of the marine bacteria, and most of the smaller invertebrate phyla occurring in the Pacific Northwest.

A large amount of temperature information, most of which is far from complete relates to mollusks. Some of the more important commercial species have been extensively studied with respect to the culture experiments. Temperature relations in the oysters, both commercial and imported, have been reasonably well studied. For the most part, these are bay forms, although beds are known from some outer coastal areas.

Mytilus californianus has been well studied with respect to community interactions and community ecology. Information on temperature range, growth range, salinity relationships, and larval stages is available. *Mytilus edulis* (the cosmopolitan bay mussel)also found on the outer coast, is one of the best known thermally of any invertebrate species found along the coast of the Pacific Northwest, but most of the published studies have come from other regions. Table 19-2 does not completely cover the thermal

Table 19-2

Physical Data on Invertebrates

Name	Age Class	Temperature	Salinity	See Source
Coelenterata				
Actina equina		41.5-43.5° C(L)		
Aequoria aequoria		0.1 - 11° C(E)		5844
Gonionemus		20-30° C(O)(R)		5845
Ctenophore				
Beroe ovata	A	34.2-36.4° C(L)		
Kinorhyneha				
Echinoderes pennaki	A	16° C (N)		3583
Crustaceans				
Branchiopoda				
Evadne normanni	A	6 - 18.5° C(R)	2-35.47‰	
Pondon polyphemoides	A	2.46-19.8° C(R)	1.05-35.1‰	
Copepods				
Calanus finmarchicus	A	0° - 10° C(R)		2695
Ismalia montrosa	A	15° - 16° C(N)		
Tigriops californicus	A	? - 39° C(R)	2-90‰ (R) 90-175‰ (L)	3650
Decapods				
Callianassa longimanna	A	8.2-13.9° C(R)	4-8‰ (R)	2184
Cancer gibbosuius	A	9.7-11.5° C(R)	33.9‰ (N)	2184
Cancer magister	A	38-75° F(R)	11-32‰ (R)	
Cancer magister	J		< 10‰ (R)	
Cancer magister	L	71° F(L) 50-57° F(O) 6.1-21.7° C(L) 10-17.8° C(O)	20‰ (L) 25-30‰ (O)	3635

Key: R = Range O = Optimum L=Lethal T = Tolerance level
N = Natural or "in situ" E = Experimental x = Data Available

Table 19-2 (cont'd)

Name	Age Class	Temperature	Salinity	See Source
Cancer oregonensis	A	11.5-13° C(E) 24-30° C(L)		5842
Cancer productus	A & L	11° C Adult spawned and larvae reared 11.5-13° C(E) 30° C(L)	33‰ ± 1‰ (E)	3279
Crangon alaskensis elongata	A	9.3-12.2° C(R) 24-27 (L)	33.8-34.3‰ (R)	5842
Crangon munita	A	11.5-13.0° C(E) 24-26° C(L)		5842
Crangon munitella		11.0-13.5° C(R)	26.6-31.6‰ (R)	
Crangon communis	A	11.5-13.0 (E) 24° C(L)		5842
Crangon spinosissima		9.3-11.4° C(R)	33.8-34.3‰ (R)	
Hemigrapsus nudus	A	11.5-13.0° C(E) 24° C(L)	4‰ - 8‰ (R)	5842
Hemigrapsus oregonensis		x	x	3585
Oregonia gracilis		9.8-11° C(?) 24-30° C(L)	3.8-34.2‰ (R)	2184
Pagurus samuelis	L	17-18° C(E)reared		
Pandalis dana	A	11.5-13.0° C(E) 24-30° C(L)		5842
Pandalus jordani	L	13 ± 0.2° C(reared)		2324
Pandalus jordani	E	50-54° F(hatching) 13 ± 0.2° C(O)	7.8-24.1‰ (R)	2295
Paracrangon echinata	A	11.5-13° C(E) 24° C(L)		5842
Petrolistles eriomerus	A	11.5-13° C(E) 24° C(L)		5842
Pugettia gracilis	A	11.5-13° C(E) 24-30° C(L)		5842

Table 19-2 (cont'd)

Name	Age Class	Temperature	Salinity & DO	See Source
Segra acutifrons		11.5-13.0° C(E) 24° C (L)		5842
Spirontocaris cristata		7.6-19.4° C(R) 13.8-14.6° C(N)	22.5-34.3‰ (R) 20.8-32.2‰ (N)	
Spirontocaris gracilis		9.6-9.8° C(N)	34.2-34.3‰ (N)	
Uca pagnax		20° C (E)		
Isopods				
Argeia pugettensis		20° C (E)		
Limnoria (gen)	A	7-23° C(T) 30° C(L) 15° C(O)		3636, 2689
Limnoria (gen)	E	9° C = 53 days incubation 21° C = 20 days incubation		2689
Limnoria ligorum	A	28° C-med. Tol.	1.0 mg/L @ 15-16° C	3636, 2689
Limnoria lignorum	E	11-16° C(R) 7-8° C (lo. dev)	1.0 mg/L @ 15-16° C	
Limnoria quadripunetata	A		0.75 mg/L @15-16° C 0.60 mg/L @ 22-26° C	3636 2710 2689
Limnoria tripunetata	A	10-30° C(R) 15° C(O)	1.0 mg/L @ 15-16° C	3628 2710
Limnoria tripunetata	E	20-30° C(R)	1.18 mg/L @ 22-25° C	2689
Barnacles				
Balanus balanus		x		
Balanus cariosus		x		
Balanus crenatus	A	7.6-8.6° C		
Mollusca				
Acmea digitalis		42° C		
Acmea persona		3.4-31° C(R)		3788 3772

Table 19-2 (cont'd)

Name	Age Class	Temperature	Salinity & DO	See Sources
Acmea scabra		42°-44° C(L)		3772
Adula californiensis				3633
Botula falcata		15° C(O) 5° & 20°C dev. stopped	32.2‰ (O) DO max. @ 20° C DO inc. @ 35.3° C	 2839 2839
Brachidontes demissus plicatulus				
Callistoma costatum		60° C air temp. 10-13° C(N)		
Crassostrea gigas		10-20° (N) much other information		3796
Crassostrea virginica	A	10 & 20° (N) much other information much temp. information under culturing		
Crassostrea virginica	E & L	Temp. & Development		5840 3783
Cymbulia peronii		35.2-35.7° C(L)		
Limacina helacina	L			3807
Littorina (gen)				3506
Littorina scutulata		34-36.5° C Lower Limit	16-20‰ lower limit	2385
Littorina sitkana		34-36.5 (R)	16-20‰	3506
Macoma		7.8-9.7(R)	29.2-31.4‰ DO 4.3-6.1 ml/L	3751
Mytilus edulus		82-106° F(L)? 77° F(O) much other ecol. temp. infor.	O_2 max. @ 20° C	2839 2798
Mytilus californianus	A	7°-28° C(R) 15-20° C(O)	17-45‰ (R) well studied 12 & 55‰ (L)	2330, 2225, 2228
Mytilus californianus	L		21.5‰ Lo survival	2228
Octopus vulgaris		33.7-36.0° C		
Ostrea edulis		15° C gametogenesis	much other information	3789

Table 19-2 (cont'd)

Name	Age Class	Temperature	Salinity & DO	See Source
Patella aspersa			Low Q_{10} 15-20° C	2693
Patella vulgata			Low Q_{10} 15-20° C	2693
Placopecten magellanicus		21.0-23.5° C(L) upper lethal raise		3764
Placopecten magellanicus		• C/5° C inc. in acclimation temperature		
Pododesmus cepio		15° C (Gametogensis)		3789
Pterotrachea cornata		39.2-42.5° C(L)		
Siliqua patula		24° C; 51.5-63° F		3635
Tegula fundbralis		60° C air 10-13° C(N)		
Tethys lanorina		40.0-40.5		
Tresus capax		9° C?	30.5‰ (O)	3388
Echinodermata				
Dendraster excentricus		x		3012 3043
Pisaster ochraceous		10-16° C(N)(R) 12-18° C 21° C(T)		5823 3286
Strongylocentrotus franciscanus		7.4° C(N)	17.10 chlorinity(N) 7.85-8.55 mg/L	2302
Strongylocentrotus purpuratus	A	8-23.5° C(R)Lab 25° C(L)		3295 3286
Strongylocentrotus purpuratus	E	13-20° C(R) 25° C(L) 5° C & 30° C no fertilization		2835 5861 2798

knowledge because we consider this species primarily a bay form. *Mytilus* larvae are relatively sensitive to environmental changes, and have been recommended as a standard for toxicity tests (De Ben, 3857).

Incidental temperature studies for the mollusks *Macoma* spp., and *Littorina* spp. are also known.

Excellent temperature and other physical information exists for several Arthropods. *Calanus finmarchicus*, a cosmopolitan form has been studied in other regions. The wood-boring isopod genus *Limnoria* rivals *Mytilus* in the amount of temperature information known. The destruction of wooden structures by this genus has been the subject of much study. Information on rates of boring with increased temperatures, O_2 consumption, survival, reproduction, and population dynamics have been studied. The validity of this information applied to specimens of this genus on our coast is unknown because many of these studies have been done elsewhere, under different environmental conditions.

The barnacle genus *Balanus* has been quite extensively studied and information on temperature, especially, as it relates to the zoogeography of this genus is published. Although some of the species are cosmopolitan, most of the studies were done in Europe and may have limited value.

The most important decapod crustacean which is well known thermally is *Cancer magister*, the dungeness crab. This species has been very well studied in many respects. At least partial temperature information exists for all life stages: it has been reared in the laboratory and the thermal tolerances of the adults are reasonably well understood. *In situ* studies, especially of larval forms, present one type of study which is needed. Such studies are necessary to predict the distribution, the expected yield or the effects of a coastal outfall. *Cancer productus*, a closely related species has also been reared in the laboratory, but due to its lack of commercial importance, has not received the attention given *C. magister*.

A small amount of temperature information is available for three other genera of decapod crustaceans, *Crangon*, *Pagarus* and *Pandalus*. The latter two genera have been reared in the laboratory.

The kinds of information available for some of the common species of the Echinodermata is perhaps of better quality than for most of the other groups of organisms. The urchin genus *Strongylocentrotus* is represented in this region by three species. Two of these *Strongylocentrotus purpuratus* and *S. fransiscanus* occur commonly from Washington to Southern California. A third, *S. droebachiensis* is the common form in Puget Sound and is also found on the outer coast of Washington and on the Atlantic coast. *Strongylocentrotus purpuratus* has been commonly used as a laboratory test animal for numerous physiological, biochemical and histological studies. We have not attempted to summarize these types of studies but have concentrated on pertinent life history and temperature studies. The reason for the large number of studies on this species is due to its large size, common occurrence, ease of collection, and readily obtainable reproductive cells for developmental studies. The importance of *S. purpuratus* to the decline of the kelp forests in Southern California also led to many detailed investigations of this species.

Experiments by Farmanfarmaian and Giese (2835) indicate that *S. purpuratus* does not acclimatize beyond the upper limit of its temperature range of 5 - 23.5° C. (The Crinoids have also been shown similar in this respect.) Temperatures of 25° C were lethal even after acclimation at 20° C for four days. This species also exhibits a rather sharp upper tolerance boundary. It appears healthy and normal at 23.5° C but is killed at 25° C. Acclimatization to lower temperatures, however, did occur. The same study by Farmanfarmaian and Giese also presented information on the fertilization and development in *S. purpuratus*. Animals developed normally between 13 - 20° C but at 5° C and 30° C no fertilization membrane or development occurred. The low temperature of 5° C was not deleterious but 25° C was lethal to the eggs. Reproduction is thought by Boolootian (5836) to be independent of temperature.

Gonor (3338) made internal temperature measurements on *S. purpuratus* on the outer coast of Oregon. When the internal temperature rose above 26° C for 3-5 hours on several successive days, a heat kill resulted. This heat kill was a natural occurrence and was attributed to the occurrence of spring tides at a period of maximum solar heating for this region.

Limited information on oxygen utilization by the purple urchin is presented by Farmanfarmaian and Giese (2835). Salinity tolerances of this genus have not been specifically studied; however, the echinoderms in general are considered to be unable to tolerate low salinities (Boolootian, 3286).

Such studies suggest that the urchin *S. purpuratus* is very sensitive to temperature changes. Since it is not presently conceivable that large volumes of the coastal region in the Pacific Northwest would be heated above 25° C, the upper lethal temperature of the purple urchin may not be as important as knowing the effects of the rate of change of temperature within the viable range of this species.

Strongylocentrotus fransiscanus and *S. droebachiensis* have not been subjected to such extenisve studies although they are also frequently used as laboratory test animals.

Information on the effects of temperature on the thickness and structure of the tests of *Dendraster excentricus* is the only temperature information located for this species of sand dollar (Raup, 3012) although a goodly amount of information was available on the natural history of this species. Only scattered incidental temperature information was found for the asteroid, *Pisaster ochraceous*. It was observed that this starfish seldom experiences water below 10° C or above 16° C, but it tolerates air temperatures of 21° C in the laboratory for 3 hours (3286). At 12-18° C it can survive for 18 months without food (5283). Such information is not adequate to determine the effect of temperature on this species.

The most frequently studied holothuroids from our area are *Parastichopus californiensis* and *Cucumaria curata*. Most studies on this group centered on behavior, ecology, natural history, or physiology.

To date, the work done on temperature requirements and tolerances of marine vertebrates has been minimal. For mammals and birds, this lack of knowledge may not be critical for they are homeothermic animals and can stand a very wide range of temperatures. Most of the birds along the Pacific coast undertake extensive migrations, spending their summers in the Arctic and their winters along the California, Mexican, and South American coasts. Some birds are perennial residents along the Pacific Northwest coast and so obviously can withstand the large seasonal changes in temperature. For the most part offshore marine birds are unstudied.

The mammals, such as the whales and sea lions, also migrate long distances, some from Arctic to sub-tropical waters as a normal part of their life cycles.

Of all groups studied the largest amount of temperature information was found for the marine fishes. The anadromous Salmonids have been extensively reviewed, and temperature studies, expecially those pertaining to rivers and fresh waters are numerous. A recent review of the Pacific salmon is to be found in Parker and Krenkel (3222). We have therefore omitted the Salmonids from our temperature discussion. However, Chapter 20 does contain a review of the coastal migrations and feeding of Pacific salmon.

We have recorded (Table 19-3) temperature range information for some life stage of thirty-one (31) species of marine fishes, of which approximately 50% are for adult stages. For some of these data, it is not known for which life stage the information was obtained. Only eight species had information for more than a single life stage; *Trachurus symmetricus* and *Engraulis mordax* (Anchovy) had information recorded for adult, juvenile, and larval stages.

Table 19-3 Summary of Physical Data on Fish

Name	Age Class	T. Range	Upper Lethal T.	Optimum T.	H_2O etc. & Nat. Env. T.	Temp. Misc.	Medium Tol. Limits Temp/ O_2 - cont.	O_2	Salinity	Salinity Misc.	See Sources
Alosa sapidissima	A	16-25° F									5614
Alosa sapidissima	J	45-70° F									
Alosa sapidissima	J	55-70° F									
Artherinops affinis oregonia		12.8-28.9°C									
Brachyistius frenatus		13-19° C							26-32‰ R		
Bram raii					57° F						
Clinocottus globiceps							Max. Surv. 26°C Q_{10} = 3.6		max. 75‰ 12° C L.	Tolerated 44‰ 26°C	2687
Clinocottus recalvus							Q_{10} ≈ 2.9				
Clupea harengus pallasi		20.8-24.7°C									2650
Clupea harengus pallasi	E	"Large"			Nat. Hatch 3-6° C	Hatch Exp. 9-14° C			R="Large"		
Cymatogaster aggregata	A								20-100‰ R		5802
Cymatogaster aggregata	J								25-36‰ R		5802
Engraulis mordax	A					Spawn Threshold 11.5-12.0°C					
Engraulis mordax	A			14.5 & 20.0°C	8.5 - 25.0°C	Spawn, 13°C					
Engraulis mordax	L	10.0-19.7° C		14.0 - 17.4° C							
Engraulis mordax	E	9.9-23.3° C		13.0 & 17.5° C					in situ 32‰	26‰	5549
Embiotocid					13° C	Unfavorable 19°C			19-31‰ R		5502
Fundulus heteroclitus		40.5-42	40.5 - 42° C								
Gadus macrocephalus		2 - 11°C									
Girella nigrans		11.8-27.0°C									
Hippoglossus stenolepis		2°C-north 10-11°C-south			3-8°C	Breeding 2.3-3.5° C				Breeding 33.5-34.1‰	5764, 5766 5772
Hippoglossus stenolepis	L			1-10°C		Development 3.5-6.5°C					
Leptocottus armatus		12-29.5°C							37.5-67.5‰ R Max. 67.5‰ 12° C		2687
Merluccius productus	L & E	10.6-15.0°C			47.5-67.3°F						

Oligocottus maculosus		12-26.5° C					Q_{10}=2.1		21-75‰ R, max.75‰, 12°C		2687
O. snyderi		2-28°C	30°C						1-50‰		
Osmerus mordax		2.3-18°C	21.5-28.5°C							25‰	
Parophrys vetulus*[1]											
Parophrys vetulus See Below	E	2.3-13.8°C	Extremes 2.3-18°C	Viable Hatch 6.5-10°C	10.6 ± 0.4°C	Hatched at 4-13° C		Consumption 0.560g/embryo/hr.	viable hatch 20-32‰	Hatch 10-40‰	
Parophrys vetulus	E					Won't hatch at 2° C			in situ 20-34‰	28‰	
Pholis clemensi		8.8-10.5°C									
Platichthys stellatus	E					Embryo Devel. 12.5°C					
Psettichthys melanostictus	E					Hatch 7-9° C					
Quietula y-cauda			max. critical 37°C			Mar. 37.4+.1°C & Sept. 42.3+0.3°C					
Raja diaphanea			28.6 & 29.0°C								
Raja erinacea			30.2°C (2 small) 29.1-29.5°C (2 large)								
Raja radiata			3 died at 26.5-26.9°C							30‰	
Remicola muscuram					14° C						
Roccus saxatilis	A	45-80°F									5614
Roccus saxatilis	J	55-70°F				Can't tolerate 45°F					5614
Sardinops sagax (caerulea)		11-27.4°C				Spawns 12.5-16.5°C					3818
Sardinops sagax (caerulea)						Dev. impaired 13°C					
Sebastodes alutus					4-5°-14°C	Spawn. 3.8-4.2°C					5755
Squalus acanthias			28.5 - 29.1° C								
Thunnus alalunga		16.3-22.8°C									
Trachurus symmetricus	A				10-19.5°C						
Trachurus symmetricus	L				14-16° C	Spawn. 14-15.5°C					
Trachurus symmetricus	E	14 - 16° C		15.5°C	10-19.5°C						5741

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*[1] Parophrys vetulus - development time: 50% hatching ranged from 3.5 days at 12°C and 25‰S to 11.8 days at 4°C and 25‰ S. Between 6-12°C development time to 50% hatching was delayed by salinities above and below 25‰. At 4°C hatching seemed to be accelerated by salinities greater and smaller than 25‰.

Key

Nat. Hatch. = Natural Hatch conditions
Hatch Exp. = Hatch Experiment conditions
T. = Temperature
Max. Surv. = Maximum Survival
R. = Range
L. = Lethal

General information about the temperature of the water of the natural environment of fishes is also occasionally found in the literature. Information on breeding and spawning especially for commercial species, although meager, is best known for this group. For marine fish the scarcity of temperature data becomes more important. Many studies have revealed that temperature is an important factor in the development, longevity and distribution of various species. However, the information is woefully incomplete. Obviously, the fish are living in areas whose temperature is suitable to their life cycle and diet. But in very few cases is it known how much of an increase or decrease in temperature a particular species can tolerate without upsetting its delicate metabolism, disturbing the development of its young, and altering its own position in the food chain.

The summary of available temperature information clearly indicates the need for high quality temperature measurements, on a wide variety of outer coastal marine species. Especially important would be studies on early life stages and effects of change in temperature on coastal habits such as feeding and migration. Such studies will be useful only if sufficient background information is simultaneously collected to make comparisons and inferences. Concentrated efforts must be made to determine the critical organisms from a biological, economic, and practical standpoint and obtain as much in situ temperature information as possible. It is evident that one of the first goals to do this type of research will be the development and standardization of methods. A similar finding was derived by Parker and Krenkel (3222) who made the following statement:

> "The authors would like to stress the need for future investigators to conform to a standard methodology in determining temperature effects on the biota. For example, information on maximum lethal temperatures is rather useless unless simlutaneous data are collected on the acclimating time, the length of time the fish (and other organisms-authors) are exposed to temperature, the rate of change of temperature, the size of the animal, the condition of the organism, the salinity and dissolved oxygen concentration and the concentrations of ions which might be synergistic or antagonistic to the effects of increased temperature (Doudoroff, 195[illegible]). Furthermore, even if the animals die or were dying at these temperatures, many experiments do not disclose if sublethal, irreversible physiological reactions had occurred well below the so-called upper lethal limit (de Sylva, 1969)."

Other Factors

Temperature is not the only factor which affects the distribution and abundance of marine organisms. Physical factors such as salinity, dissolved oxygen, light, turbidity and pH are also important. Previous reviews of the literature on the combined effects of temperature and salinity are limited to Kinne's (2378) discussion. In discussing the effects of physical factors on marine organisms, we must remember that animals and plants do not compartmentalize the various physical and biotic factors in their environment. The organisms see the combined effects of all of the complex interacting environmental factors and a small change in one may have a significant effect on some other factor (Kinne, 2379; Hedgpeth and Gonor, 3856).

Our review of supplementary physical factors was not as extensive as that for temperature; we feel a quick perusal of Tables 19-1, 19-2, and 19-3 will indicate the appalling lack of supplemental factors for almost every species.

Salinity information was found for 28 species of marine invertebrates from our area (Table 19-2) and 12 species of fishes (Table 19-3). These data can generally be broken into two groups--optimum salinity which generally corresponds to a given temperature and salinity range which, like the temperature range, is not comparable between species.

Oxygen data are meager. Several studies confirmed the increase of O_2 consumption with increasing temperature. The importance of O_2 may be a matter of concern only seasonally, if at all. Information on pH is recorded for seven species of marine algae, and this in an abstract of an unpublished report by Blinks (2949).

In view of the fact that there is so much variance in the amount and the quality of temperature, salinity and other physical data on the organisms of the outer coast of the Pacific Northwest we strongly recommend referring to specific entries in Chapter 20, or to appendix 8.

The effects of other factors such as chemical pollutants are found in Chapters 15, 16, and 17.

Chapter 20. BIOLOGY OF SELECTED NORTHWEST SPECIES OR SPECIES GROUPS

by James E. McCauley and Danil R. Hancock

This chapter presents comprehensive summaries of the information collected for 20 selected species or species groups which we concluded were important. Importance is a highly subjective concept often reflecting the views of the writer. It, therefore, becomes necessary for the writer to state his position when selecting a group of species which he wishes to call important. To derive such a list we reviewed the amassed literature available on species from the region of our study. This literature involved more than four thousand species; most included simply reports of the species occurring in the region. From this literature review a checklist of the species from the region was compiled; this list, with appropriate annotations, is included in this report as Appendix 8. Among the species included in this list, a few stood out as being much more thoroughly studied than the rest. The reasons for this more intensive study were usually rooted in the economic importance of the species, but in some cases were related to abundance or to other less specific factors. Although 20 species or species groups are included in this Chapter, we do not intend to infer that these are the only important species in the region of our study. The listing is comprised mostly of fishes, probably because this group has been subjected to a great deal of study by State and Federal fishery agencies and by other interested groups. Many species have been omitted from this Chapter simply because there is not enough information available to allow us to assess their importance in the nearshore marine community.

In this Chapter the ecology of each of the 20 species (or species groups) has been described. Data on such environmental factors as temperature and salinity have been discussed fully but information of other factors sometimes is limited to a literature reference. Whereas most of the literature used to derive the big checklist (Appendix 8) has referred to the Pacific Northwest, more distant sources were included in these detailed studies.

The assembled information included here should be useful in quickly determining significant basic facts about some of the important organisms of the region and, perhaps more importantly, should point out those areas in which more research is needed.

We wish to acknowledge the assistance of Dr. Emory Sutton, Mrs. Nancy Blind, and Mrs. Dianne Dean for their assistance in compiling this information.

The species (or species groups) are arranged alphabetically by scientific name except for the group Phytoplankton which comes first. The following are included:

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1. Phytoplankton

by Emory Sutton

The knowledge of the inshore marine phytoplankton of the area may be divided into three categories (1) taxonomy and distribution (2) community structure (3) physiological responses to elevated temperature. It is advantageous to discuss these three categories separately so that the need for additional work may be easier to assess.

Taxonomy and species distribution

A review of the literature concerning species distribution reveals that a large number of species are present wherever a taxonomist is found, and that the phytoplankters in the areas between the focal points of taxonomists are poorly known. The region with which we are concerned is located between two such focal points and it must be inferred in many cases that an organism exists in this area because it exists both at the northern and southern sites of taxonomic study. It may be further pointed out that both of the extensive studies (Cupp off southern California; 7000, and Gran and Angst in Puget Sound, 3527) were done over thirty years ago. Since that time taxonomy has been largely a by-product of some other aspect of planktonology and not the result of work by a full-scale taxonomist. By contrast, Hendey (7039) has done quite a thorough study of the British coastal waters. This work was begun in the mid 1930's however.

What is needed for this area is a sampling program which would give an adequate picture of what organisms are found in the coastal waters of the region under consideration. This would take at least a year since different organisms appear at different times of the year. The validity of the flora of Puget Sound (Phifer, 7017; Gran & Angst, 3527) might be questioned at this time due to the influence of increased population, since 1930, in the Puget Sound region. Another problem with the species distribution analysis is the fact that few people are active in the field of taxonomy. The University of Washington and Oregon State University both have preserved samples from off the Oregon coast but so far no publications have come from these samples which represent years of data.

Community structure

This aspect of marine phytoplankton research cannot actually be separated from part (1) since the factors which control the distribution of species also act to control the community composition at any given location. It is this phase of research which should concern the individuals engaged in determining the possible effects of elevated temperature on the marine phytoplankton. So little is known about the effects on community structure of a changing environment that we cannot even predict with any certainty what will happen when we change just one factor, temperature. It has been observed (7032) in Monterey Bay, California, that when the temperature of the water warmed from 12°C to 14°C the diatoms were displaced as the dominant organisms by species of *Peridinium*, *Gonyaulax*, and *Ceratium* with accompanying red tide and bioluminescence. When studying the effect of temperature variation on phytoplankton, the situation is complicated by the combined interactions between the organism, the community of light, nutrients, and temperature. This is the one point upon which many phytoplanktonologists and ecologists are agreed (Oppenheimer, 7041). In the laboratory the light and nutrient variables may be controlled and the effects of temperature examined before any predictions may be made on the possible effects on the phytoplankton community of the introduction of effluent of high temperature into the environment.

Physiological responses to elevated temperatures

So little has been done in this area that in a recent publication Strickland and Eppley (7038) devoted less than two pages to the effects of temperature on the kinetics of marine phytoplankton growth. A number of investigators have looked at the thermal limits of some marine phytoplankters but oftentimes they were looking at different aspects of the organism's responses to thermal stress.

A partial listing of the work and findings of investigators using organisms found in this area follows. Kain and Fogg (7002), while studying *Asterionella japonica*, found that this organism had an optimum temperature for growth at 20-25°C and a maximum of less than 30°C in culture. This is considerably higher than that found in the natural situation in the region under consideration. However, the effects of adding nutrients, trace elements, and vitamins to the medium must be considered in such laboratory cultures. *Asterionella japonica* is very common in the inshore region and needs more attention before conclusions are drawn in regard to the effects of thermal pollution. Thomas (7003) used another organism which occurs in this region, *Chaetoceros gracilis*, and found that this organism had a lower limit of 11°C and an upper limit of 41°C with an optimum between 23 and 37°C. *Skeletonema costatum* has been the subject of considerable research on the influence of temperature on physiological processes. This organism is important in the neritic phytoplankton and is of ubiquitous distribution. Jorgensen and Nielsen (7006) found that photosynthesis was little affected by temperature in the range 7-20°C. Curl and McLeod (7008) found this organism to be tolerant of temperatures 5-30°C and reported that Matsue had found a tolerance to 37-40°C. Jitta *et al.* (7009) studied the cell division of *Skeletonema costatum* and found that it would tolerate temperatures from 6°C to more than 28°C. Braarud (7012) found that this organism grew well at 17-18°C. Ryther and Guillard (7015) found that *S. costatum* grew from 5 to 25°C.

The problem of assigning a label of "important" to a species of the phytoplankton is nearly impossible whether it be for scientific or economic reasons. Little is known about the effect on the higher trophic levels of changing phytoplankton community structure. Some studies have been done on the feeding preferences of copepods with respect to diatom shape by the Bureau of Commercial Fisheries Laboratory at Auke Bay, Alaska. It has been suggested that the diatom *Chaetoceros armatum* might be a principal food organism for the razor clam along the Washington coast. If this is so then this organism should be investigated with respect to its physiological ecology. The diatom *Skeletonema costatum* is important because of its ubiquity and its role in phytoplankton research. *Chaetoceros decipiens* is important because of its abundance off the Oregon coast. A group of organisms which is probably important but largely unknown are the various unicellular flagellated forms which are not studied because of the difficulty involved. These small flagellates abound in the estuaries and inshore regions of the area especially in the spring and summer months. A concentrated effort is needed to gain some knowledge as to the distribution and physiology of these organisms as well as their interrelations with the higher trophic levels.

The fact is clear that there can be little possibility of assigning importance values to the phytoplankters until there is more known about their interrelationships with the next higher trophic level. The fact that an organism which occurs in abundance in an area may be displaced by another organism when the environmental conditions change is important.

In conclusion it might be said that the need at present is to find out what organisms are occurring in the area, the dynamics of change in population size, and the dynamics of change in community structure and then to find how a change in temperature changes the above. The phytoplankton are small and easily overlooked when concentrating attention on larger economically important species.

2. *Clupea harengus pallasi* (Valenciennes) (Pacific Herring)

by Nancy Blind

The Pacific herring is probably the most important fish in the northeastern Pacific area. Not only is it important because of the large commercial fishery it forms but also because of the great number of animals that feed upon herring eggs, larvae and adults.

The range of the herring is from Kamchatka to the San Diego area (Schultz and DeLacy, 2049), with the largest fishery being in British Columbia and Washington. The herring is fished commercially in the fall when it begins to move inshore toward the spawning grounds (Thompson, 2444).

Spawning takes place primarily in bays and estuaries along the Pacific coast, in winter and spring. In British Columbia, spawning is from mid-February to mid-April, with the peak occurring slightly earlier in southern British Columbia than in the northern area (Taylor, 5530).

The eggs are laid in the intertidal zone from approximately 0 to 4 meters above the low tide level (Taylor, 5530). Some sources extend the area of egg deposition to a depth of 30 ft. (Fulton, 3635). The spawn adheres to gravel, pilings, oysters and vegetation such as *Zostera marina*, *Phyllospadix scouleri*, *Sargassum muticum*, *Fucus evanescens*, and *Laminaria* sp. (Taylor, 5530).

Temperature and Larvae

Hatching time of the eggs has been shown to be temperature dependent. In the natural environment, the water temperature is around 3-6°C and at this temperature, hatching occurs in 20-22 days. When the temperature is raised to 9-10°C, hatching takes 14-15 days, and when increased to 12-14°C, the eggs hatch in 9 days (Nikitinskaya, 5673). The larvae are very small, thin and nearly transparent and are easily sucked into water intake pipes (Fulton, 3635). They can withstand large ranges of temperature and salinity. At the end of the first year, the larvae leave the bays and sounds for the open ocean (Taylor, 5530).

Migration

Maturity is reached after 2, 3, or 4 years and herring may live 8 years (Clemens and Wilby, 2390). Tagging of juveniles showed 52% homing after 2 years at large and 64% after 3 years, by sub-district, which is defined as the region occupied by an adult population. Adults showed 81% and 92% homing (Hourston, 5666). Analyses of vertebral counts and tagging data also show that there is more than one population along the west coast of Vancouver Island. Each has a separate run and there is very little mixing between populations (Tester, 5680). The largest migratory populations form the greatest part of the fishery (Taylor, 5678).

Feeding

The herring is primarily a plankton feeder (Clemens and Wilby, 2390) and (Fulton, 3635). However, in Little Port Walter, Alaska, herring were observed feeding on Oncorhynchus gorbuscha fry. The greatest predation, in this instance seemed to be in daylight (Thorsteinson, 5681).

Predators

Most importantly, it is a food source for innumerable marine animals. Herring eggs are eaten by fish and other filter feeders such as jelly fish, combjellies and crustaceans (Clemens and Wilby, 2390). Primary predators on herring eggs are the marine birds. It has been estimated that mortality due to bird predation ranges between 56% and 99% (Taylor, 5530). Losses up to 39% within the first 3 days after spawning were calculated from predation by the glaucous-winged gull and the herring gull alone. This was calculated for eggs laid mainly on vegetation. Of the two, the glaucous-winged gull consumed less vegetation and more spawn than did the herring gulls (Outram, 5661). Larvae near the surface are also preyed upon heavily (Taylor, 5530).

Larger herring are eaten by sharks, fishes, waterfowl, seals and sea lions (Clemens and Wilby, 2390). Stomach analyses of 1004 salmon (Oncorhynchus tshawytscha) caught in the year of October 1954 to October 1955, showed that 12.7% of the stomach contents was Clupea pallasii (Merkel, 5669). Herring is the principal food of the Alaskan fur seal during the spring (Scheffer, 5674). Ninety-nine percent of the food of 148 mature female Callorhinus ursinus taken in January and March was C. pallasi. Also, one harbor porpoise (Phocoena vomerian) taken had fed entirely on herring (Wilke and Kenyon, 5682).

Very little has been done on temperature tolerances and we found no information concerning the effects of various chemicals or pollutants on the herring.

Other studies on the Pacific herring include:
Fecundity - Piskunov, 5671; Katy and Erickson, 5664; McHugh, 5668.
Egg description and fertilization information - Yanagimachi, 5690, 5691, 5692; Yanagimachi and Kaneh, 5693.
Fishery - Taylor, 5530; Kithama, 5665; Tester, 5529.
For catch data see - U. S. Fish and Wildlife Service, Current Fishery statistics; U. S. Fish and Wildlife Service, and Statistical Digest (Pacific Coast Fisheries).

Synonyms: Clupea pallasii, C. mirabilis

3. Cymatogaster aggregata (Gibbons) (Shiner perch)

by Nancy Blind

The shiner perch, a fish of relatively small commercial value, is of particular interest because it is so numerous along the Pacific coast and because it bears live young. Sometimes called the pile perch, it is common around docks and pilings. According to Schultz and DeLacy (20[illegible]) the range of *C. aggregata* extends from approximately Port W[illegible]gel, Alaska to Todos Santos Bay in Baja California.

Life history

The reproductive cycle of this fish has been the subject of much study. Copulation occurs in mid-summer; sperm is retained in the ovary of the female until December when fertilization takes place (Wiebe, 5800; Eigenmann, 5736). The embryos are then held until parturition in mid-summer.

Temperature studies

Temperature and photoperiod seem to have a definite effect on the reproductive cycle of *C. aggregata*. Increasing or long photoperiod, such as in late winter, spring or early summer, results in spermatogenesis, development of secondary sex structures and reproductive behavior. Warm temperatures also enhance this. Cold temperatures and short photoperiod, as in winter, result in testicular restitution and growth of spermatogonia (Wiebe, 2484).

In the female, warm temperatures as in late summer and early autumn aid in oocyte formation. Cold temperature as in late winter helps oocyte maturation. Early gestation is aided by cold temperatures but warmer temperatures are required later on (Wiebe, 2484).

Adults regulate to dilutions from 20% to 100% sea water, but the ability of the young to regulate was proportional to their stage of development. The youngest stages could only regulate well between 25-36% sea water due to greater permeability and less efficient salt secretory mechanisms (Triplett and Barrymore, 5802). *Cymatogaster aggregata* is more resistant to changes in oxygen content or carbon dioxide content of sea water than either the salmon, *Oncorhynchus kisutch*, or the herring, *Clupea pallasii*. This was in keeping with the fact that the alkali reserve of the blood plasma of *C. aggregata* changes very rapidly with changes in carbon dioxide tension of sea water (Powers and Shipe, 2575).

The pile perch is found in shallow waters during the summer and in deeper waters in the winter. They eat small crustaceans and other invertebrates (2390). There is a record of a massive kill of C. aggregata in British Columbia due to hydrogen-sulfide production during a dredging operation (Hourston and Herlinreaux, 5797).

Other important studies include:
Reproduction - Wiebes, 5800; Turner, 5801; Eigenmann, 5736; and Wilson and Millemann, 5799.

4. Cancer magister Dana (Dungeness crab)

by Diane Dean

The Dungeness crab is one of the largest edible crabs of the United States. It is also known as the Pacific crab, market crab, commercial crab, and white crab (3361, 3342), ranging from the Alaskan Peninsula (Aleutian Islands) to Magdalena Bay in lower California (Rees, 3275; MacKay, 3363). It occurs within bays and estuaries as well as on the open ocean floor preferring sandy or sandy-mud bottoms but found on all types (Waldron, 3232; Dewberry, 3356; MacKay, 3363). The crab is found at varying depths. Rees (3275) stated 12-120 feet and Dewberry (3356) stated from low tide to an average of 50 fathoms. Other reports are from 2-20 fathoms (Hipkins, 3361), 40-60 fathoms (Cleaver, 3333) and from intertidal zone to 93 fathoms (Kenyon and Scheffer, 3372). Butler (3611) has compiled an extensive bibliography for this species.

Life history

The diet of the Dungeness crab consists of small fish, shrimp, small crabs, marine worms, isopods, amphipods, barnacles, clams, oysters and other shell fish, preferring fresh, live food or recently dead to stale food (Dewberry, 3356; Waldron, 3282; MacKay, 3363). It is mainly carnivorous and will eat other crabs in the soft-shelled stage (Dewberry, 3356).

Reproduction and life cycle

The female is usually 90 to 100 mm wide and about two years of age at sexual maturity (Cleaver, 3333; Butler, 3329). The males reach sexual maturity at a carapace width of 116 mm. Breeding activity begins at about 140 mm carapace width or when the crab is 3 years old (Butler, 3329). At the onset of maturity there is a definite segregation between males and females as shown by lack of uniform distribution (Cleaver, 3333; Dewberry, 3356). In British Columbia mating takes place from April to September on the tidal flats. Males are polygamous (Dewberry, 3356). In Washington, mating takes place during May and June (Cleaver, 3333). Hatching takes place from December to June with the height in March in British Columbia (MacKay, 3356). In Oregon waters hatching takes place from December to April (Trask, 3279).

Larvae or "protozoea" swim to the surface of the water and moult to zoea stages. Crab larvae are attracted by light and at times in May and June in Washington waters they swarm near shore at the surface of the water. Later in life they show an aversion to light (Cleaver, 2039).

Poole (3273) reared larvae in the laboratory and watched them develop through six larval stages, five zoea and one megalopa which metamorphoses directly to the first crab instar (Reed, 3274). Development occurred in salinities from 26-30‰ at a temperature of 51 °F. Total development time from egg to first crab instar was 111 days. High mortality during transitions appeared to be due to inability of larvae to break completely away from casts. Under natural conditions sand may aid in shedding casts. Food for the zoea was Artemia nauplii. The megalops fed on larger brine shrimp (Poole, 3273). Natural development in the ocean appears to take from 128 to 158 days. Under natural conditions the zoea feed on microscopic plants and minute marine animals (Dewberry, 3356). Crab larvae are eaten by a number of aquatic animals, among them fish such as silver salmon, herring, pilchard, mackerel and wolf eel, and also sea birds (Fish Commission of Oregon, 3319; Waldron, 3282; Dewberry, 3356).

The megalops is cannibalistic and preys on small crustaceans, crab eggs, and dying and dead planktonic life (Dewberry, 3356). The megalops stage shows up about the month of August (Dewberry, 3356; Butler, 3332) and eventually loses its ability to swim, sinking to the sea bed where it burrows into the sand and mud and continues to molt (Dewberry, 3356).

Trask (3279) reared Cancer magister and Cancer productus in the laboratory and indicated how to separate the larval stages of these two species. He did not describe in detail the physical conditions under which they were reared.

Temperature and salinities

MacKay (3397) reported that the crabs' distribution is bounded by surface water isotherms of 75 and 40°F and one report of temperature-salinity range for the Dungeness crab is from 38-65°F and from 11-32‰. Crabs can't live in fresh water, and adult crabs retreat before a freshet. Juvenile crabs appear to have a wider tolerance for they are commonly found in estuaries with salinities less than 10‰ (Cleaver, 3333).

In culturing zoeae, Reed (3092) found the optimum lab-culturing ranges of temperature and salinities to be 10.0-13.9°C and 25-30‰ respectively. Faster zoeal development with lower survival rate occurred at 17.8°C and 20-30‰. The effects of temperature and salinity alone on zoeae didn't seem to cause large fluctuations in zoeal survival, but reduced temperature and resulting prolonged zoeal development combined with current transport may effect survival of post larval crabs.

The Dungeness crabs are extremely susceptible to drying (Cleaver, 3333), but can be kept alive for 2-8 hours if their gills are kept moist (Hipkins, 3361; Dewberry, 3356).

Migration

Both sexes show characteristic migratory patterns (Dewberry, 3356). A predominant south to north movement occurs during spring and summer months (January to June). Two other migratory patterns are (1) on and off-shore and (2) coast wise. Tagged specimens travel average distances of 10-12 nautical miles after six months' freedom. One long migration was recorded from Grays Harbour to Tillamook Bay, Oregon, a distance of more than 148 km (Cleaver, 3333). Waldron (3282) found that the average non-directional distance travelled was 15 km (range 0-250 km). Crabs released in bays averaged non-directional distance of 8 km (range 0-150 km). Snow and Wagner (3278) and Butler (3331) also made tag-migration studies.

Predation

Crab larvae have numerous enemies, and the adult is also subject to prey. After molting it is defenseless. Enemies include the conger eel, wolf eel, cod, dog fish, halibut, skate rays, nurse hound sharks, marbled sculpin, rock fish, octopus and other crabs. Cannibalism takes place when one crab is in the soft-shelled state (Waldron, 3282; Dewberry, 3356; Gray, 3358).

Economic importance

Crabs are economically important. The Pacific Coast states produce over 15,800 metric tons of shell crab with a value of at least $5.5 million to the fishermen (Poole, 3273). The crabs are marketed as frozen, whole or dressed crabs and cooked meat is sold fresh or canned (Walburg, 3287). California leads in catches followed by Oregon, Washington and then Alaska (Rees, 3275).

Other important studies include:
Molting and regeneration - Dewberry, 3356; Phillips, 3405; MacKay, 3363; Walburg, 3287.
Mating behavior - Snow and Nielson, 3277; MacKay, 3363.
Egg development - MacKay, 3363.
Growth and development - Butler, 3222 and 3321; Dewberry, 3356; MacKay and Weymouth, 2067.
Physiological studies - Jones, 3362; Davenport, 3344; Collip, 3129; Goode, 3318.

Needed research:
Although much work has been done on Cancer magister, no "in situ" studies describing the effects of environmental changes on the life cycle and ecology were found.

5. Engraulis mordax (Girard) (Northern anchovy)

by Nancy Blind

The northern anchovy is probably the most abundant fish in the northeastern Pacific ranging from the Queen Charlotte Islands in British Columbia to Cape San Lucas, Baja California. The largest concentration is found from San Francisco Bay to Magdalena Bay (Baxter, 5697). Meristic characters such as the number of gill rakers, vertebrae and fin rays, indicate three subpopulations along the Pacific coast (McHugh, 5696). The first population extends from British Columbia to central California, the second from southern California to northern Baja California, and the third from central to southern Baja California (Baxter, 5697). There seems to exist for each characteristic an inverse relationship between the mean number of meristic elements and the water temperature during the fixation period in the larval stage (McHugh, 5696).

The anchovy, a pelagic fish inhabiting coastal waters, is found well below the surface during the day and in the upper layers at night (McHugh and Fitch, 5621). No north-south migrations have been noted but the fish move offshore during fall and winter and inshore during the spring (Baxter, 5697). Tagging studies indicate no significant movement for this species (Wood and Robson, 5706; Messersmith, 5703). At times when the water temperature is warmer than usual, fewer adults are found in inshore waters (Baxter, 5697).

Biology

Spawning occurs over the entire range but is concentrated from Point Conception, California, to Point San Juanico, Baja California. The peak of the spawning period is in late winter and early spring, however spawning does occur in every month of the year. Although anchovies spawn as far as 480 km from shore, most spawning takes place within 90 km. Each female spawns 2-3 times each year. The eggs and larvae are pelagic and are found in the upper layers (Baxter, 5697).

Off California, eggs are found in temperatures ranging from 9.9 to 23.3°C with most between 13.0 and 17.5°C. Ten percent of the spawning takes place below 13.0°C (Baxter, 5697). Bolin (5726) indicated that spawning occurred regularly at 10°C. The threshold temperature for spawning seems to be 11.5 or 12.0°C. Fertilization is immediate and apparently very successful since unfertilized eggs are uncommon (Baxter, 5697).

Hatching occurs in 2-4 days depending on the water temperature. Larvae taken in California are found from 10.0 to 19.7°C with 95% being present in temperatures from 14.0 to 17.4°C. Some were taken in the upper 23 meters but the main concentration seemed to be between 24-48 meters. The larvae are 2.5 to 3.0 mm at hatching (Baxter, 5697) and colorless, in contrast to most fish larvae which have some pigmentation (Ahlstrom, 5724).

The growth rate is very rapid, however, there seems to be a decrease in growth rate from August to November (Baxter, 5697). Clark (5694) found that fifty percent of the females reach maturity in 2-3 years. All are mature by the time they reach a length of 150 mm or by 4 years. The anchovy is relatively short-lived, with a life span of approximately four years.

Feeding

Food is primarily organisms less than one mm in length filtered from the water. Larvae feed on crustaceans, especially copepods. Adults feed also by biting on larger organisms. In this sense, they are somewhat cannibalistic, since they occasionally prey on smaller anchovies. Although they seem to prefer larger organisms, anchovies will not abandon filtration unless other organisms are in abundance (Baxter, 5697).

Ecology

Along the Pacific coast, there is a close competition between the anchovy and the sardine (Sardinops sagax). The competition seems to be that of two animals occupying the same trophic level (Ahlstrom, 5698) and is evident from the larval stages of both fish. Both sardine and anchovy are abundant in the same area and eat nearly the same food (Baxter, 5697). Indications are that anchovy larvae can consume larger food particles than can sardine larvae (Berner, 5725), perhaps, giving it an advantage. However, it will be noted that the sardine is present in the Gulf of Mexico, an area which has not yet been invaded by the anchovy (Ahlstrom, 5698). Since 1954, the sardine population along the Pacific coast has greatly decreased while the anchovy has increased. Recent surveys show that eggs of the sardine are outnumbered not only by the eggs of *Engraulis mordax*, but also of *Merluccius productus*, *Trachurus symmetricus* and *Sebastodes* spp. The anchovy now appears to be the dominant species.

Predation

Enemies of the anchovy include nearly every species of predatory fish. Not much is known about the percent of the anchovy population consumed by the various species. Available data shows that in California, the anchovy comprises 12.8% of the food of *Senola dorsalis* and 29.1% of *Oncorhynchus kisutch* (Baxter, 5697). It is also the main food in summer and fall for *Roccus saxatilis* in San Francisco Bay (Johnson and Calhoun, 5695).

Temperature studies

From 1955 to 1964, samples of anchovy taken along the California coast were taken in water temperatures ranging from 8.5 to 25.0°C. Of 617 samples from northern California to Magdalena Bay, 75.9% were taken between 14.5 and 20.0°C. From southern California to northern Baja California, 340 samples were taken in 8.5 to 21.5°C and 72.5% of these were between 14.5°C and 18.5°C. Of 277 samples taken in central to southern Baja California waters of 13.0 to 25.0°C, 65% were from water between 17.0 and 21.5°C (Baxter, 5697).

Economic importance

There are two fisheries for the anchovy: the commercial and the live bait fishery. The commercial fishery is concerned with fresh, frozen, or salted fish for human or pet food; dead bait; feed for hatcheries or mink farms and reduction of waste parts to meal and oil. The anchovy comprises 98% of the live bait fishery (Baxter, 5697). It is mainly used in fishing for albacore. Most indications are that the anchovy fisheries can be exploited to a greater extent in the future (Prater, 2571).

Other important studies are:
Fecundity - Baxter, 5697.
Eggs - Ahlstrom, 5724.
Photoreception and light intensity - O'Connell, 5700; Loukashkin, 5704.
Catch Statistics for California (other states not available) from
U. S. Fish and Wildlife Service, Statistical Digest. No. 55-60.

6. Eopsetta jordani (Lockington) (Petrale sole, brill)

by Nancy Blind

In older literature, the name may appear as Hippoglossoides jordani (2416).

The range of the petrale sole extends from Unalaska to San Diego Bay (Schultz and DeLacy, 2049) however it is fished commercially only from Santa Barbara, California, to Hecate Strait, British Columbia, with the main area of concentration being in northern Washington and southern British Columbia (California Fish and Game, 5729).

Feeding

Eopsetta jordani is usually found on bottoms of a mixture of mud and sand. Although little is known about its feeding habits, the sole is reported to eat herring, sandlance, anchovies, euphausiids, rockfish, flatfish, and zoarcids (Clemens and Wilby, 2390; California Fish and Game, 5729; Cleaver, 5773).

Spawning and growth

Harry (5525, 5775) indicated that spawning takes place from November to March throughout the range with the heaviest spawning being in December and January. The eggs are probably free floating; very little information is available on development (California Fish and Game, 5729).

Comparison of meristic characters indicate the existence of two main stocks in the northern Pacific area: one extends from Hecate Strait to Trinidad Head, California, and the other one ranges from central to southern California. This is accounted for by the stable conditions of temperature and salinity within the areas where spawning takes place. South of Point Conception, the salinity is similar but the water temperature is 1.0°C higher (Best, 5774).

Migration

Although there is little mixing of the two populations, tagging studies indicate a north-south spawning migration (Ketchen and Forrester, 5793; Barraclough, 5789; California Fish and Game, 5729). There is a northerly inshore feeding migration in the summer and a southerly, offshore spawning movement in the winter. Spawning seems to take place in waters of about 200 fathoms (California Fish and Game, 5729). The average rate of migration is 3.75 km/day with the maximum for an individual being 7.1 km/day (Best, 5774).

Additional important information on the petrale sole includes:
Trawling and catch data - Alverson and Pruter, 5735.
Feeding - California Fish and Game, 5729
Age, Growth and Size range - Alverson and Pruter, 5735; California Fish and Game, 5729; Cleaver, 5773; Harry, 5775; Ketchen and Forrester, 5793.

7. Hippoglossus stenolepis Schmidt (Pacific halibut)

by Nancy Blind

The Pacific halibut, Hippoglossus stenolepis Schmidt, forms the basis for a significant industry along the Pacific Northwest coast. It is widely distributed throughout the north Pacific, occurring from Japan north into the Bering Sea and then southward along the coast to northern California (Schultz and DeLacy, 2049). The southern limit of the commercial fishery is Cape Mendocino, California (Bell and Best, 5766).

Life history

Information concerning the life history of the halibut is not extensive. The fish occurs from very shallow water to depths around 1100 meters although it is most numerous between 55-400 meters (Clemens and Wilby, 2390). Along the Washington and Oregon coasts, no halibut are taken commercially deeper than 367 meters. Most of the fish were caught on the inner continental shelf and the number taken decreased with increased depth. Halibut comprised 15% to 42% of all flounders caught on the inner shelf (Alverson, 5735).

Spawning

Spawning takes place during the winter, usually from November to January, at depths of 275-400 meters (Clemens, 2390). The fertilized eggs and early larvae rise to midwater depths and are carried great distances by the ocean currents. The northward drift of the larvae is counterbalanced to some extent by a general southerly movement of the adults (Bell and Best, 5766). Studies in the Gulf of Alaska show considerable movement eastward (Thompson and Henington, 5765), presumably toward spawning grounds over the continental slope (Thompson and Van Cleve, 5764).

Russian studies in the Bering Sea indicate that the halibut breeds in water of temperature 2.3° to 3.5°C and salinity of 33.5‰ to 34.1‰ (Novikov, 5772). Thompson *et al.* (5764) report that the larvae develop at 3.5-6.5°C.

After six to seven months, the larvae become demersal, usually during May and June. Thompson and Van Cleve (5764) gave a very detailed account of this as well as the taxonomic aspects of the development of the eggs and larvae. Apparently, the young halibut occupy somewhat shallower water than do the adults (Novikov, 5772). Females grow faster than males and have a longer life span. Catches in the Bering Sea consisted of fish from 1 to 2 years of age. Males reach maturity sometime between their seventh and thirteenth year and at lengths of 90 to 140 cm (Novikov, 5772). Off the Oregon and Washington coasts, the range was 23 to 176 cm with an average of 59.2 cm (Alverson *et al.*, 5735).

Food

Clemens and Wilby (2390) list food of the halibut as: various fish, crabs, clams, squids and other invertebrates. There is some indication that diet varies with age (Novikov, 2772).

Predators

Some of the halibuts' natural enemies are the sea lion (Eumetopeas stelleri), the "ground shark," the lamprey and other halibut (Thompson, 2442).

Temperature and Distribution

The geographic distribution of the halibut has been analyzed with regard to temperature. Throughout the north Pacific it occurs in boreal waters of 3-8°C. This also seems to be correlated with the ocean current pattern. The southern limits of the commercial fishery occur at 10-11°C and the northern limit is 2°C (Thompson and Van Cleve, 5764). Optimum temperature for the halibut in the Bering Sea was given as 1-10°C. This was considered to be a wider range than evidenced for more southerly individuals (Novikov, 5772). Abundance of halibut broods and the temperature from 1910 has seemed to have a positive relationship 10 to 12 years later (Ketchen, 5767).

Other important studies on the Pacific halibut include:
Size range - Alverson *et al.*, 5735
Fecundity - Alverson *et al.*, 5772
Egg size and composition - Thompson and Van Cleve, 5764
Growth - Southward, 5769
Food and Feeding - Thompson, 2442
Fishery - Thompson, 5762; Burkenroad, 5763; Southward, 5769, 5770
Catch statistics - see U. S. Fish and Wildlife Service statistical digest for the years of interest.
Also see the publications by the International Halibut Commission for additional information concerning catch statistics, regulation and state of the fishery.

8. Macrocystis spp. (Giant kelps)

by Diane Dean and Danil R. Hancock

Macrocystis, the giant kelp, forms the dominant plant community of sub-littoral, temperate, boreal and austral areas (MacFarland and Prescott, 5817) growing along the North and South Pacific coasts of the Western Hemisphere between 40°N and 60°S latitude.

In shallow (8-25 m) rocky regions of southern California Macrocystis pyrifera is the dominant species in the climax community, while further north M. integrefolia increases in relative dominance. In the Pacific Northwest, especially Puget Sound, the closely related Nereocystis luetkeana (the bull kelp) becomes the dominant kelp.

Macrocystis attaches to rocks by means of a holdfast. Growth tends to diminish with depth and below 30 m attached plants become quite sparse (Anonymous, 5815; Leighton et al., 5816). Kelp, both directly and indirectly, is an important food source for man and for nearshore animals. The extensive holdfast system and the dense foliage canopy at the surface provides both food and shelter for marine organisms and therefore the beds comprise prize fishing areas (Leighton et al., 5816). "Drift" seaweed, of which Macrocystis often comprises a substantial portion, is of importance and has often been observed on the sea floor in areas much deeper than it normally grows (Anonymous, 5815).

Although agarophytes and edible seaweeds are often present in abundance, giant kelp is the only marine plant in the California region directly utilized by man and 90,000 metric tons (wet) are harvested annually (approximate value, one million dollars). It is also used as fertilizer, for food additives, and the upper parts are harvested for certain chemical constituents (North, 5811).

Most of our knowledge concerning the giant kelp communities are the result of studies in southern California to determine the causes for their decline since 1940.

Growth and photosynthesis

The giant kelps extend from the bottom into the zones of bright illumination providing a large surface area of photosynthetic tissue and creating a zone of plant productivity in deeper water.

The stipes, pneumatocysts and blades are photosynthetic (Clendenning, 5812), but the vegetative blades are the main site of photosynthesis.

The sporophyll is located directly above the holdfast. Spore liberation apparently continues throughout the year eventually giving rise to gametophytes. Gametophytes are dioecious, the female producing the egg which can be fertilized by the sperm to produce the spermatophyte, known as kelp. It requires about 1/2 year from the time of spore liberation to the development of a sporophyte 18" high (Anonymous, 5815).

Temperature, salinity and water quality

Kelp growth probably increases about two-fold for a 10°C rise in temperature (Leighton, 5816). Leighton cited Clendenning who found a Q_{10} of 2.0 for kelp photosynthesis and North who obtained a value of 1.7 for frond elongation (Leighton et al., 1966).

Temperatures above 18°C may affect kelp adversely, increasing with the length of time the high temperature is maintained. Beds seem to deteriorate in warm water later in the summer and early autumn but will revive in cold conditions (North, 5809).

There seems to be considerable geographic variation in the degree of sensitivity of kelp to warm water (Anonymous, 5815). The strains of Macrocystis in southern California exhibit sensitivity to elevated water temperature and large quantities of kelp are lost in summer if water temperature exceeds 20°C and persists for several weeks. A strain of kelp labelled "O" in Baja California has greater resistance surviving temperatures of 24°C (North, 5809).

In a 90-day transplant experiment, plants kept at 15 meters (temperature 15-18°C; photosynthetically active light 5% of surface intensity) doubled in area every 21 days and in length every 24 days.

Plants growing at comparable depths on natural substrates doubled in length every 24 to 34 days (Haxo and Neushal, 5818). For additional information on temperature and transplants see North and Neushal (5809).

Salinity does not seem to have a detrimental effect on photosynthesis following an 18-hour exposure to salinity of 25‰ higher or lower than natural seawater. In a 5-day incubation period at 20°C photosynthetic capacity was lower in samples that had been exposed to seawater diluted 10% to 25% with distilled water. Water temperature was held between 14-17°C. At 18°C the kelp did not do well (Anonymous, 5815).

Discharge of effluent may cause changes in salinity and/or temperature which could be significant in the immediate vicinity of an outfall, but certainly not at greater distances. In fact, investigations into the effects of discharged wastes on kelp have revealed that no chemical or effluent tested was sufficiently toxic to account for great losses in kelp (Anonymous, 5815).

Predation

Grazers use the kelp beds as a main supply of food. More obvious grazers include fish, the abalone Haliotus fulgens; the wavy top, Astraea undosa; the turban, Norriaia norrisii; the opaleye, Girella nigricans; crustaceans; gastropods, and echinoids. Two important urchins Strongylocentrotus franciscanus and S. purpuratus feed on the sporophylls of the kelp (Leighton et al., 5816; Anonymous, 5815). These sea urchins seem to be one of the most damaging herbivores because they sever the stipe at the base (Leighton et al., 5816). Sewage may encourage urchins and cause a change in the ecological balance between seaweed and grazers.

Predators of the urchins include: sheephead fish (Pimelometopon pulchrum), the sun star (Pycnopodia helianthoides), the agile sea star (Astrometris sertulifera), and the sea otter (Enhydra lutris). Only the otter appears to be an effective controlling agent, but it occurs in insignificant numbers (Leighton et al., 5816).

Leighton *et al.* (5816) showed that a rise in temperature from 5-15°C can increase the average daily algal consumption by *S. purpuratus* from about 1.7 to 6.4% of body weight. Above 17°C the consumption rate declined. Over the range where rates increased, consumption by urchins increased much more rapidly than the kelp growth rates. Increased demands by grazers may occur during warm water seasons when feeding rates may rise more rapidly than plant growth rates.

Other important studies on the giant kelp include the following:
Measurements on respiration and chlorophyll - MacFarland and Prescott, 5817
Translocation of organic matter - Sargent and Lantrip, 5819
Growth - North, 5811
Transplantation - Anderson and North, 5813
Standing crop - MacFarland and Prescott, 5817; Anderson and North, 5813
Grazing pressures - Leighton *et al.*, 5816

For further information on giant kelp see:

Clendenning, K. A. 1958. Quart. Prog. Rpt. Kelp Inv. Prog. Univ. Calif. Inst. Mar. Res. IMR ref. 58-3, Oct-Dec, 1957, p. 6.

Clendenning, K. A. 1959. Physiological Studies on Giant Kelp. Kelp Inv. Prog. Quart. Prog. Rpt. IMR ref. 59-9, Univ. of Calif.

I. M. R. 1963. Kelp Habitat Improvement Proj. Final Rept. 1962-63. Univ. Calif. Inst. Mar. Res. I. M. R. ref. 63-13.

Leighton, D. L. 1960. Quart. Prog. Rept. Kelp Inv. Prog. Univ. Calif. Inst. Mar. Res. I. M. R. ref. 60-8, Jan-Mar, 1960, p. 28.

9. *Merluccius productus* (Ayers) (Pacific hake)

by Nancy Blind

The biology of the Pacific hake has recently been reviewed in detail by the U. S. Bureau of Commercial Fisheries (3081, 3082).

The hake is pelagic and sometimes demersal. It ranges from the Gulf of Alaska to the Gulf of California but it is commercially concentrated from south Vancouver Island to Baja California. It is usually taken near the bottom anywhere in shallow waters to depths around 800 meters, and particularly between 45 and 500 meters (Alverson and Larkins, 5712), (Nelson and Larkins, 3081).

In Washington, the hake is most numerous from Grays Harbor to the Columbia River at depths of 37 to 92 meters, most occurring within 18 meters from the sea bed (5714).

Spawning

Spawning is pelagic in the open ocean and the greatest concentration of eggs and larvae seems to be at about 200 meters. Larvae are abundant very near the coast to 380 km from the coast off southern California (Alverson and Larkins, 5712). Some hake larvae have been found as far out to sea as 650 km. Along the California coast, hake larvae are the most numerous species taken (Calif. Dept. Fish & Game, 5729). The largest concentration of eggs and larvae occurs at temperatures between 10.6° and 15.0°C in southern California (Ahlstrom and Counts, 5728). Nelson and Larkins (3081) state larvae most often found with or near the thermocline at temperatures 47.5-65.3°F. An obvious lack of knowledge concerns the distribution and ecology of the juvenile (1-3 yr. old) hake (Nelson and Larkins, 3081). Adult hake usually mature between 3 and 4 years. There seems to be a high natural mortality among adults which has been estimated to be around 40% (Alverson and Larkins, 5712).

Migration and schooling

The adult population occupies the northern part of the range in spring, summer, and fall; and the southern part in the winter (Alverson and Larkins, 5712). This may be associated with spawning which occurs primarily in January through April (Calif. Dept. Fish & Game, 5729). During the summer, length-frequency data shows a lack of juveniles off Washington, but an abundance off southern California. This, too, indicates some north-south migration. Migration patterns suggest that there is one homogeneous stock off the Pacific coast. Genetic studies also indicate a single population throughout the range (Nelson and Larkins, 3081). This population may perhaps aggregate during the spawning season (Alverson and Larkins, 5712).

Feeding

Off the Washington coast, the main foods of the hake are the euphausiids Thysanoessa spinifera and Euphausia pacifica, and the pink shrimp Pandalus jordani (U. S. Fish and Wildlife Service, 5713; Nelson and Larkins, 3081; and Gotshall, 5730). In addition, the hake also eats some small fishes and squids (Clemens and Wilby, 2390). Alton and Nelson (3082) have recently published a complete review of the feeding of the Pacific hake.

Predators

No specific major predators have been listed for the hake. The dog-fish shark, Squalus acanthias, has been observed eating hake (Shippen and Alton, 5639) and it can be assumed that probably any one of the large predators will consume hake.

The interest in commercially fishing for hake has risen considerably in the last ten years. With the use of special techniques, the hake can be easily and profitably reduced to meal and oil (Dyer et al., 5731; Alverson and Larkins, 5712). Also, it has recently been appearing on the market in small numbers as fillets. It is still a large source of animal food (Best and Nitsos, 5732). The standing stock in the summer off Washington and Oregon has been estimated to be between 550 and 1,100 thousand metric tons. This means that the population is second only to the anchovy, Engraulis mordax, in number (Alverson and Larkins, 5712). There is no reason to doubt that the hake may become even more important in the future.

Other important information on the Pacific hake includes:
Depth and Distribution - Calif. Fish and Game, 5729; U. S. Fish and Wildlife Service, 5713.
Fecundity - MacGregor, 5637.
Vertical Migration - U. S. Fish and Wildlife Service, 5713.
Catch Data - U. S. Fish and Wildlife Service statistical digest for years of interest.

10. Microstomus pacificus (Lockington) (Dover sole)

by Nancy Blind and Danil R. Hancock

The Dover sole, which ranges from Alaska to Guadalupe Island, Baja California, is one of the most important species of flatfish along the Pacific coast. It inhabits deeper waters than most flatfish and is found on muddy bottoms (Roedel, 2567; Clemens and Wilby, 2390). One fishery survey found Dover sole from 2 to 1090 meters although catch rates were highest between 180 and 365 meters. Off Washington and Oregon it was a dominant species, comprising 56-91% of the flatfish catch. It was found to be less abundant and in shallower waters farther north (Alverson et al., 5735).

Spawning

Spawning takes place from November to March (Harry, 5775). Some references give the time as December to February (Hagerman, 2572). The larvae are pelagic. According to Hagerman (2572) eggs and young tend to drift south and shoreward on currents.

Growth and development

Very little information is available on the growth and development of the Dover sole. The trawls catch fish whose lengths range from 11 to 63 cm (Alverson et al., 5735) but 14 in. (approximately 35 cm) seems to be the accepted market minimum (Harry, 5775). The females are larger than the males (Westrheim and Morgan, 5776). Mean size seems to increase with depth (Alverson et al., 5735). The sole eats mainly invertebrates that inhabit mud (Hagerman, 2572).

Migration

No north-south migrations are indicated for this species (Harry, 5528) but tagging studies have revealed a seasonal inshore-offshore migration (Harry, 5528; Westrheim and Morgan, 5776). This probably accounts for the fact that in California, the Dover sole fishery is most important in the summer (Best, 5785). Tagging in the Willapa area in Washington showed that inshore recoveries were made between

55-110 meters during June to September and offshore recoveries were made between 180-300 fathoms from November to April. Most of the fish tagged were males (Westrheim and Morgan, 5776). Another study found that fish tagged in shallow water in the summer were recovered in 365 meters in the winter (Harry, 5528).

There seems to be a limited exchange of stocks between British Columbia and northern California (Westrheim and Morgan, 5776). In the Willapa tagging study, only seven sole were recaptured at distances more than 55 km from the original tagging area. Also from this study, the annual mortality was estimated to be 0.58 (Westrheim and Morgan, 5776).

Other information on Dover sole includes:
Fecundity - Harry, 5775.
Fishery - Best, 5785; Westrheim and Morgan, 5776.

11. *Mytilus californianus* Conrad (California sea mussel)

by Diane Dean

The California sea mussel is also known as the big mussel or rock mussel. It ranges from 18° N to 54° N (Alaska to Mexico) (Keen, 2207). Reish (2898) pinpointed the two extremes of their range at the Aleutian Islands in Alaska and Isla Socorro in Mexico. On the Oregon coast these mussels are abundant at Netarts Bay, Cape Mears, North Siletz Bay and Tillamook Head (Edmondson, 2345).

The habitat of the mussel is the intertidal zone on rocky exposed coasts (Reish, 2898). The supposed stenobathic habitat of the California sea mussel has been questioned by Berry (2542). He stated that the mussel can survive long periods of immersion in aerated sea water of widely different salt concentrations and further that the mussel has the ability to live and thrive well below the tidal zone; in fact as far down as 90 meters.

The mussel occupies a wide vertical zone in the marine intertidal environment. Research on respiration showed that high-level mussels have higher metabolic rates during submergence and post-exposure periods. One consequence of high tide existence is an increase in metabolic function above that found in low-level animals (Moon, 2335).

Salinity, temperature and physiology studies

Studies of sex cells and larvae suggest that they are affected by salinities less than 29.6‰. Fertilization usually occurs readily at 21.5‰ but survival of the larvae is low. Turbulence as well as salinity may be a factor in determining the mussel's distribution (Young, 2330).

Aeration is a factor very beneficial to prolonging the life span of the mussel in water of any salinity that does not kill them in a short time. Under conditions of continuous aeration, the mussel possesses a wide range of tolerances for heterosmotic conditions (17‰-45‰ S). Fox et al. (2228) found that mussels immersed in water of salinities about 12‰ and less die in 4-7 days. Hypertonic solutions of 55‰ or more prove fatal also. Crowding individuals in an aquarium has a deleterious effect because of the accumulation of nonvolatile waste products.

Temperature is another factor which affects the California sea mussel. Naylor (2798) stated that intertidal molluscs show tolerances for higher temperatures; the higher up the shore they are found, the longer periods they are normally exposed to air. Sublittoral species are much less tolerant. Mussels of higher latitudes had higher rates of ciliary pumping action than did low-latitude species at lower temperatures. A positive correlation between growth rate and water temperature was found by Fox and Coe (2229), but there was a decrease in growth during the month with the highest temperature.

Optimum growth temperatures are 15-19°C with a decrease of growth at 20°C. Temperatures above 20°C are less favorable for general metabolism (Coe and Fox, 2225). Other temperature data listed by Coe and Fox (2226) showed that mussels exhibit a rapid increase in size at temperatures of 17-20°C. Growth continues less rapidly at 14°C or lower. Feeding continues at temperatures as low as 7-8°C and as high as 27-28°C.

Rao (2891) studied rate of water propulsion in the mussel as a function of latitude. He found that (1) shell weight is a function of latitude and, consequently, of the mean annual temperature (increases with increasing latitude), (2) absolute rate as well as weight-specific rate of pumping is greater at any temperature in mussels from higher latitudes, (3) rate of decline, in absolute as well as weight-specific rate of pumping with increasing size was slower in higher latitudes. He speculated perhaps this is why there are larger sized mussels in the more northern forms. The center of dispersal of species such as Mytilus californianus is in the lower latitudes.

Rao (2893) made other studies concerned with tidal rhythmicity of rate of water propulsion in the California sea mussel. Mussels exhibit a pattern of activity (measured by rate of water propulsion) which corresponds in time and degree to the tidal levels in the locality in which they live. The rhythm is independent of temperature (range from 9-20°C) and of various light conditions and no indication of a diurnal rhythm in the rate of water propulsion is apparent. Rao speculated that the frequency of the rhythm is intrinsic and perhaps inherited and suggested that the degree to which the intrinsic rhythm becomes marked and measurable depends on the amplitude of the environmental rhythm.

The California sea mussel is a mucus, filter-feeding organism. Mussels feed by extending their siphons and drawing a current of water. Their principal food supply is minute particles of organic detritus from disintegrating cells of all kinds of marine organisms (plant and animal), supplemented by living and dead unicellular organisms and living or dead gametes (Coe and Fox, 2226). Detritus comprises 4/5 of their nutrition (Fox et al., 2228). Rapid growth rate correlates indirectly with dinoflagellate populations, however, dinoflagellates can supply only a small fraction of the mussel's nutritive requirements (Coe and Fox, 2226). Calcium used in shell building is obtained from the water. The alkaline nature of the mantle next to the shell permits calcium deposition by that tissue.

Biology

Sexes of the mussels are strictly separate (Fitch, 2227). Males become sexually mature earlier than females (Coe and Fox, 2225). Female mussels produce as many as 100,000 eggs during a season (Bonnot, 2224).

According to Whedon (2329) spawning occurs at all times of the year irrespective of temperature or other external stimuli, yet at the same time he found spawning coincident with a falling rather than a rising temperature. The period of maximum spawning begins in early October followed by two lesser periods in January-February and May-June. Data indicating a definite annual spawning cycle are also in the literature (Annonymous, 2706). Spawning begins in September, increases to a maximum in midwinter and gradually declines to a minimum from May to August. Occasional spawning is observed in summer. A negative correlation exists between rising temperature and spawning in Mytilus. The major spawning season is between October and March.

Stimulation of spawning by Kraft mill effluent has been studied (Breese et al., 3810). Kraft mill effluent is highly effective in triggering spawning in the bay and California sea mussels. Stimulation does not seem to affect viability and fertilization capacity of the gametes.

Ecological studies

Hewatt (2233) studied ecological succession on an exposed rock which had been scraped clean. He stated that the reestablishment of the climax condition requires a period of at least more than 2 1/2 years; therefore, he cautioned against exploitation of mussel beds. Predators of the mussel include gulls, sharks, rays, fish, starfish, flesh-eating snails and crabs (Fitch, 2227).

The mussel affects the physical properties of the environment, (1) by removing minute material, altering turbidity and light penetration of the water, (2) by depositing feces and pseudofeces to change the character of the bottom, (3) by altering the chemical composition of the water slightly ($O_2 \rightarrow CO_2$, etc.), (4) by adding to a temporary supply of proteins, lipids and carbohydrates where it dies, and (5) by contributing to gametes and itself a food supply for fish and other invertebrates (Fox and Coe, 2229).

There are several reasons why the California sea mussel is economically important. It can be one of the greatest expenses to steam and other industrial plants by growing in large clumps and fouling intake pipes (Fitch, 2227).

The mussel is used as a food source by man (Fitch, 2227). Joyner and Spinelli (2446) stated that mussels can be readily processed into dried concentrate, rich in protein.

Other studies on the California sea mussel include:
Attachment and locomotion - Bonnet, 2224
Organic matter and soluble nutrient removal, utilization and fixation - Coe and Fox, 2226
Clumping, crawling as a distributional and competitive factor - Harger, 3753
Paralytic shellfish poisoning, Pharmacological and biochemical studies - Murtha, 2334; Schantz, 2332
Parasitological studies - Berry, 2543; Chew _et al._, 5534; Naylor, 2798; Coe and Fox, 2525
Predator prey relationship - Pilson and Taylor, 2333

Portions of the life cycle of this mussel are well studied while information on other phases, especially larval stages is less well known. A comprehensive review of the life history of the California sea mussel would be most useful. Although the larvae has been shown to be very sensitive to toxic substances, only limited information on the mussel's tolerance to temperature and other pollutants is available. Work in these areas would be advisable.

12. _Oncorhynchus_ spp. (Pacific salmon)

by Diane Dean and Danil R. Hancock

This report deals with five species of Pacific coast salmon: _Oncorhynchus gorbuscha_ (pink salmon), _O. keta_ (chum salmon), _O. kisutch_ (coho salmon), _O. nerka_ (sockeye salmon), and _O. tshawytscha_ (chinook salmon). These salmon have been intensively studied with regard to their fisheries which are primarily brackish and fresh water. We therefore placed emphasis on reviewing the coastal migratory patterns of these fishes although a succinct summary of the life cycle, biology, and ecology has been attempted. A review of the Pacific salmon has recently been published by Parker and Krenkel (3222).

Review of life history

Salmon hatch in streams, rivers and lakes of the mountainous coasts of North America and eastern Asia. They journey out to the sea where they grow to a fairly large size and then by some unknown mechanism return to their natal streams to spawn and die.

All species of Pacific salmon are anadromous, meaning the adults must migrate to fresh water to spawn. Spawning usually takes place in the summer and autumn months. Females deposit their eggs in redds (or nests) in the stream's gravel. The accompanying male fertilizes the eggs and the eggs are covered over by gravel. Hatching depends on water temperature and the particular species, but usually takes about three months. Fry absorb food from their yolk sacs and then leave the gravel in search of food. They often move downstream to a lake where they may remain for a time before going on to the sea. Seaward migration depends on the species. Some fish may go to sea as fry and some as late as two years. During summer young fish tend to occupy a single region of thermocline. Later, in autumn and winter when temperature is more uniform, a vertical distribution occurs. With the onset of spring, yearlings tend to become more active and start to school. Their movement and the current flow to outlets brings fish to stream outlets of the lakes and then they are caught in the streams. Now they are under the influence of the current. Some fish (in Georgia Strait) tend to remain in the upper less saline water. This places them in the location of the strongest seaward current. Young salmon are sometimes carried in a coastal current causing them to move in a north and northwest direction (Clemens, 2424). The time at sea and the miles they travel is as yet not definitely known. When salmon eventually reach the ocean their oceanic life spans one to four years depending on the species. As they begin to mature they change physically: (1) increasing in endocrine activity, (2) changing body metabolism, and (3) altering osmotic regulation. The fish tend to occupy water of lower salinity which will be surfaceward and shoreward. They also respond rheotactically and will be led to the rivers, whereupon they begin their upstream migration to spawn (Clemens and Burner, 2424, 3020; Foerster, 2502).

Food

Young salmon depend on plankton organisms which are abundant both in fresh and salt water (Burner, 3020). All salmon eat crustaceans, especially the pinks (2390), chum (2771), sockeye (Burner, 3020) and king (5507). Pinks also feed on squid and other fish (2390). Coho are more pelagic in feeding and accept a wider variety of food than the chinook salmon. Herring is one of the main foods but studies show that if the herring is eliminated from their diet, the salmon would turn to other food sources (5507).

Food of the Pacific Salmon.

	Pink	Chum	Coho	Chinook	Sockeye
	O. gorbuscha	keta	kisutch	tshawytscha	nerka
Plankton organisms		C			
Crustaceans	A	C	ABD	E	HJ
polychaetes		C			J
pteropods		C			J
Copepods		C			J
amphipods		C			J
euphausiids		C		F	J
Crab megolops				F	
Squids	AB			F	B
small fish	AB		AD	EF	
herring			AD	E	
sand lance			AD		
insects				G	

A - Clemens and Wilby, 2390
B - Manzer, 3032
C - Brett and Alderdice, 2771
D - Carl, 2336
E - Prakash, 5507
F - Merkel, 5669
G - Sosaki, 3144
H - Burner, 3020
J - Fulton, 3635

Temperature and salinity factors

Studies show that young chum, chinook, coho, sockeye, and pink salmon prefer salinities less than 33.6‰ and temperatures less than 15°C. They avoid water of greater than 34‰ salinity and temperatures of 20°C. Young pinks and chum have intolerance to temperatures below -0.5°C and -0.1°C is the low limit for lethal temperatures (2771). Young coho have a fairly high minimum temperature limit of 5.0-5.9°C and prefer 7°C (Manzer *et al.*, 3023). Juvenile coho have a maximum cruising speed of 0.3 m/sec at 20°C and a minimum of 0.06 m/sec at around 0°C (5513). Juvenile sockeye salmon had a maximum cruising speed of 0.33 m/sec at the optimum temperature of 16°C and a minimum of 0.12 m/sec at 0°C (5513). A high water temperature where chinook were caught was 13-13.9°C (Manzer *et al.*, 3023).

Temperature and Salinities Information on Pacific Salmon

Salinities	Pink O. gorbuscha	Chum keta	Coho kisutch	Chinook tshawytscha	Sockeye nerka
Young prefer less than 33.6‰	A	A	A	A	A
Avoid greater than 34‰	A	A	A	A	A
Temperatures					
Preferred less than 15°C	A		A	A	A
Avoid greater than 20°C	A	A	A	A	A
Complete intolerance to temperature below -0.5°C	B	B			
Lethal temperature -0.1°C low limit	B	B			

A - Clemens and Wilby, 2390
B - Brett and Alderdice, 2771

One research operation including 5,160,000 square meters off the coast of Oregon and Washington to longitude 175°C and from latitude 43°N to 60°N captured salmon in surface water temperatures of 0.5-14.5°C. No juvenile sockeye or chum were captured in water temperatures below 4.4°C. In warmer areas, the largest salmon catches were made in waters ranging from 9.4-12.8°C with the largest total catch associated with a 10°C surface temperature (Hanovan and Tononako, 2645). Chinook and coho seem to be the most resistant to high temperatures (5-24°C) while pinks and chums are least resistant. Sockeye have greater resistance to prolonged exposure to high temperatures than the latter two. None of these species can withstand temperatures below 4°C when acclimated to 20°C , nor can they tolerate temperatures exceeding 25.1°C when exposed for a week (Brett, 5568).

Sockeye are native to practically all temperate and subarctic water where summer surface temperatures range from 5-16°C and summer surface salinities are generally less than 32.2‰. Salmon occupy the upper 20-30 m (60-100 ft) strata of water (Foerster, 2502).

Spawning times:	pink	late September to early November (2390)
	chum	late in fall (2390)
	sockeye	late summer and autumn, August to November (Foerster, 2502)

Most salmon in Aleutian waters spawn in streams either in Asia or North America, exclusive of the Aleutian Islands. Migrations ultimately must be more or less west or eastward (Johnson, 2840).

Migration patterns

Not much is known concerning the migratory patterns of salmon at sea. It would seem that temperature and maturity of the fish influence their location. A change in distribution of each species may be due to maturing fish leaving the high seas for spawning grounds and immature individuals remaining and responding to various environmental factors (Manzer *et al.*, 3023). Salmon evacuate the Bering Sea and northeastern Pacific in winter where surface water temperature decreases and they move southward and eastward (Manzer *et al.*, 3023).

Columbia River fall chinook are found principally north of the Columbia River and predominant migration in the fall is to Columbia River watersheds to spawn. Tagging in Northern British Columbia and Alaska have shown large numbers of Columbia River fish.

Lower river populations must confine their ocean migrations to areas between the Columbia River and Vancouver Island. Upper river fish may not even make a long northward migration but stay in the local area through life.

Relatively few chinook are found in the ocean off the Columbia River during June and July. In winter the fish gather in the area between the Columbia River and Gray's Harbor. As the season progresses most of the fish move northward on a feeding migration while the rest turn south towards the Sacramento-San Jaoquin System. In the fall mature fish enter rivers leaving immature fish scattered along the coast. In the winter the remaining fish regroup in the Columbia River-Gray's Harbor area making a spring and summer northward migration again.

The northward shifting populations in the summer and southward movement in the winter appear to be characteristic for all North Pacific salmon. This could be due to a response to warming of surface water or differences in distributional patterns between mature and immature fish (Van Hyning, 3301).

Adult fall chinook return from the North in August and September when the current is running south. Young may be carried north earlier by currents.

Studies in British Columbia show that initial dispersion of immature fish from stream mouth up to distances of 55-74 km is accomplished within a few days. Pinks and chums intermingle and frequent the shores until mid July. Their offshore movement is gradual or irregular. Pinks have been captured up to 11-22 km from shore in September. Distribution and movement during autumn and winter is virtually unknown. Tagging in 1962 showed that in April and May fish which subsequently migrated to central coastal areas in British Columbia were to the south of their spawning streams or near the latitude of the Columbia River (45°31'N, 126°36'W). A northward movement took place next and some went far north of their spawning grounds (Neave, 3053). It is known that a concentration of sockeye occurs near the middle of the Gulf of Alaska during April and May. Distribution becomes complicated as fish go to their separate rivers (Ricker, 3116).

It is known the sockeye reproduce in North American watersheds from the Columbia River to the Bering Sea (Margolis et al., 3202). The fry generally emerge in 80-140 days (April-May) (Foerster, 2502).

Avoidance reactions of Pacific salmon to pulp mill effluent were tested. Chinook showed marked avoidance to toxic concentrations of sulphate and sulphite wastes. Coho showed reduced avoidance compared to chinook (Beak, 2152).

Studies of ocean migrations for salmon are being conducted and perhaps in the future predictions can be made.

13. Ophiodon elongatus (Girard) (Ling cod)

by Nancy Blind

The ling cod ranges from Alaska to the San Martin Islands in northern Baja California (Roedel, 2567) but it reaches its greatest abundance north of California. It lives on the bottom in rocky areas or kelp beds, particularly near a strong tidal current (Calif. Fish and Game, 5729; Clemens and Wilby, 2390). It is sometimes taken as deep as 370 meters but is found mainly in depths of around 110 meters (Calif. Fish and Game, 5729; Phillips, 5647).

Life history

The adult ling cod is rather sluggish and spends most of its time resting on the bottom waiting for prey to swim within its reach. Tagging studies by Phillips (5647) indicate that only nine percent of the population move more than five miles from the area of release. Sex does not seem to have any effect on migration, but indications are that large fish move less frequently than smaller ones (Hart, 5734).

In some regions there seems to be a shifting of spawning fish from offshore waters to inshore sub-tidal rocky reefs (Calif. Fish and Game, 5729).

Spawning

Spawning takes place from late December to February or early March (Clemens and Wilby, 2390). The eggs are guarded by the male ling cod until they hatch, around six weeks later. The larvae are about 1.3 cm long and use their yolk sac in 10 days. Very little is known about the post-larval stages (Phillips, 5647).

Growth and development

Both males and females start to mature at 63 cm in length and almost all are mature at 65 cm. Females reach 63 cm in 3 years and 65 cm in four years (Phillips, 5647; Calif. Fish and Game, 5729). Males are somewhat shorter-lived than the females, which may reach a maximum age of twenty years (Calif. Fish and Game, 5729).

Feeding

The ling cod is an extremely voracious fish and will eat almost anything. Its most common diet includes herring, flounders, hake, cod, whiting, sand lance, young ling cod, squid, dog fish shark, pollack, rockfish, crab and shrimp (Clemens and Wilby, 2390; Phillips, 5647).

Economics

Although the ling cod is an important component of the west coast fishery, there seems to be comparatively little information in the literature about it. No temperature data seem to be available and information about life history is minimal.

Other important information on ling cod includes:
Fecundity - Calif. Fish and Game, 5729; Phillips, 5647
Metabolic rate and biochemical studies - Pritchard, 2097
Egg description - Phillips, 5647
Survival rates - Chatwin, 2211
Catch statistics - U. S. Fish and Wildlife Service, Statistical Digest, for years of interest
Fishery - Reeves, 2089; Calif. Fish and Game, 5729; Phillips, 5647.

14. Parophrys vetulus Girard (Lemon sole or English sole)

by Nancy Blind

Parophrys vetulus ranges from Unalaska to Sebastian Vizcaino Bay in Baja California (Roedel, 2567). More specifically, its range is given as being from 28°30'N, 115°00'W to 54°30'N, 164°00'W (Alderdice and Forrester, 2453). The range for the commercial fishery is from Santa Barbara, California, to Hecate Strait, British Columbia (Jow, 5778). It is particularly important in Oregon and Washington, but declines toward the northern end of its range (Alverson *et al.*, 5735). Almost all lemon sole caught are sold as fresh fillets (Calif. Fish and Game, 5729).

Biology

The lemon sole is found over muddy or sandy bottoms, often from 20 to 50 fathoms (Clemens and Wilby, 2390; Ketchen, 5522, 5523). A trawling survey, primarily along the Washington coast, found the sole in depths from 1 to 299 fathoms (Alverson *et al.*, 5735).

The spawning season is given by Budd (5737) as being from January to May, whereas Harry (5775) believes it to be from November to March. Alderdice and Forrester (2453) listed the lemon sole as spawning over a four-month period ending in late March or early April with the peak in early February.

The eggs are bouyant, pelagic, spherical, and transparent (Budd, 5737; Alderdice and Forrester, 2453; and Calif. Fish and Game, 5729). The eggs float at the surface but if not fertilized within 15 to 30 minutes, they begin to sink (Orsi, 5541).

Temperature and salinity

Alderdice and Forrester (2453) performed experiments to determine the effect of temperature and salinity on the eggs and larvae of *Parophrys vetulus*. Their study produced the following information: The eggs were held at various combinations of salinities from 10‰ to 40‰ S and temperatures of 4° to 12°C. Hatching occurred at every salinity and temperature. Development time to 50% hatching ranged from 3.5 days at 12°C and 25‰ salinity to 11.8 days at 4°C and 25‰ salinity. Between 6°C and 12°C, development time to 50% hatching was delayed by salinities above and below 25‰ whereas at 4°C, hatching seemed to be accelerated by salinities greater and smaller than 25‰.

In regard to lengths of the larvae, the greatest mean length (2.92 mm) was obtained at 25‰ salinity and 8°C. The total number of larvae hatched seemed to be greatest at this level also. The oxygen consumption was calculated to be 0.560 g per embryo per hour.

Salinities and temperatures encountered in the natural environment were 20‰ to 34‰ salinity and 2.3 to 13.8°C. A change of 1°C was found to be approximately equivalent to a change of 4‰ salinity. Experimental evidence showed that 90% viable hatch was obtained at salinities of 20-32‰ and temperatures 6.5-10°C. Although salinity may perhaps modify the effects of temperature on early development of P. vetulus, it appears to have little direct influence on egg survival. Temperatures at the extremes of the geographical range for this species are 2.3°C and 18°C. These areas are probably populated through larval drift and some adult migration. Irregularity of catch and abundance over the area would suggest that other factors such as water transport and availability of suitable areas for continued larval development also influence egg and larval survival.

It has been noted that weak year classes are produced in years when the water temperature is higher than normal since the elevated temperature speeds up embryonic development. Thus the developing larvae would not be carried to the proper rearing grounds by the currents. Low temperature prolongs the pelagic stage allowing the larvae to be carried to the rearing grounds (Ketchen, 5522).

The young, when hatched, are extremely weak swimmers and hence are at the mercy of the water currents. They survive for approximately 14 days on the yolk sac (Orsi, 5541). The larvae are carried about in the surface currents for about 6 to 10 weeks and then go to the bottom (Calif. Fish and Game, 5729). Usually they are found close to the intertidal zone and then move into deeper water as they mature (Clemens and Wilby, 2390). In one bay survey, only young fish

(2 to 18 cm) were caught in the bay. Presumably no adults were present. All but 5% of the young fish migrated from the bay to the ocean in the late summer and early fall of their first year (Westrheim, 5542).

Feeding

Adult lemon sole feed mainly on invertebrates which inhabit muddy bottoms, such as worms, molluscs, small starfish, small crabs, brittle stars, clam siphons and shrimps. Occasionally they consume small fish. Sharks, skates and lingcod are the lemon sole's main predators however, no one species can be designated as the major predator (Calif. Fish and Game, 5729; Clemens and Wilby, 2390).

Distribution and migragion

Various studies have indicated the existence of several stocks of *Parophrys vetulus* along the Pacific coast. Two broad groups have been defined; one ranging along the Washington coast and the other centering around Cape Blanco to Cape Mendocino (Anon., 5777). In addition, two major stocks have been described off British Columbia; one in the Strait of Georgia and the other around Hecate Strait. Within these main stocks, there appear to be substocks (Forrester, 5781). Four stocks have been described for California (Jow, 5778).

Along the Washington and British Columbia coasts, a spawning migration seems to take place. Fish tagged in Washington went south along northern Oregon; some as far as northern California, in the fall and then north in the spring. All recoveries were made over the continental shelf in depths less than 100 fathoms (Pattie, 5782). Off British Columbia, the fish go north to feed in the summer. The adults then are found around 20 fathoms. In the winter they are somewhat deeper. Extensive migrations seem to be more characteristic of the females than the males (Forrester, 5781). There appears to be little mixing between stocks (Ketchen and Forrester, 5546).

Other important information on the English sole includes:
Egg description - Budd, 5737
Fecundity - Harry, 5775
Catch statistics - see U. S. Fish and Wildlife Service, Statistical
  Digest, for the years of interest
Fishery - Palmen, 2063; Holland, 5779; Smith, 5780; Forrester, 5781
Growth and development - Van Cleave and El Sayer,-5783; Smith,
  5790; Calif. Fish and Game, 5729; Alverson *et al.*, 5735;
  Harry, 5775.

15. Pandalus jordani Rathbun (Pink shrimp)

by Diane Dean

The pink shrimp Pandalus jordani is distributed along the Pacific coast from Unalaska in the Aleutians to Southern California (Rathbun, 2328). San Diego is the extreme southern extension of its range (Dahlstrom, 2327). The pink shrimp is the dominant species along the Oregon and Washington coasts, but north of British Columbia P. borealis becomes the dominant species. Ronholt (2294) stated that P. jordani, P. borealis and Pandalopsis dispar all appeared to occur in concentrations adequate to support large-scale commercial operations.

The pink shrimp have been taken at depths ranging from 37 to 450 meters, but are commonly caught within the depths of 110-180 meters. They generally occur in areas which are characterized by green mud (Ronholt, 2294) or glauconite mud (Alverson et al., 2324).

Food habits of P. jordani are not well known. Dahlstrom (2327) stated that the food of the pink shrimp was believed to be microscopic material found in green mud bottoms. The only available temperature information on the adults (Alverson et al., 2324) reported that shrimp were caught in water having a temperature of 42.1-46.7°F off Oregon and Washington and further that no apparent relation was noted between catches of pink shrimp and differences in bottom water temperature within that range.

Some comparisons of different species of shrimp were made as to depth range (Anonymous, 2322). Spot shrimp collected in Dabob Bay were found to occur only in the lower four rows of collector bags. These were concentrated in the area between the bottom and one meter. Pink shrimp and side-striped shrimp were found in all openings of the bag particularly from .03 to 1 meter off bottom.

That pink shrimp undergo a vertical migration to the near-surface water during hours of darkness is well documented.

They have been located off the Queets River, 11 to 15 meters below the surface over bottom depths of 79 to 81 meters. Before midnight there was none caught and at 0412 hours there was no yield (2321). Shrimp off the Washington coast may move off the bottom at night. One night drag in autumn produced 30 kg pounds of pinks while 4 night drags in spring produced an average of 2.5 kg per drag. Alverson et al. (2324) also mentioned vertical movements in response to diurnal changes. Day-time drags always produced more shrimp (Tegelberg, 2325).

Magill and Erho (2296) reported that the species is small, with the average length being 10 cm. Shrimp are measured by count per pound and Dahlstrom (2327) listed figures of approximately 100/lb. or 60-180/lb. while Magill and Erho (2296) listed 70-150/lb. Dahlstrom (2327) reported the average age of shrimp to be about 4 years.

Pink shrimp are protandric hermaphrodites beginning life as males and changing to females (Magill and Erho, 2296). During the period when the males transpose to females the shrimp are termed "transitionals" (Ronholt and Magill, 2326). Normally, the individuals reach maturity as mature males at 1 1/2 years but up to 50% of this age group may be mature females by the second autumn (Butler, 2323). Some confusion exists on the breeding cycles of the pink shrimp. Certain instances in Oregon have been noted where shrimp continued as males throughout the second winter while the majority of the year class transposed to females and became gravid (Magill and Erho, 2296). Tegelberg and Smith (2325) noted 18 month old females bearing eggs in the fall. They had either functioned early as males or had skipped the male stage.

In distinguishing males from females after larval development two points, including the male organ, are evident on the ramus of the male. Atrophy of the male sex organ and lengthening of the tip of the ramus take place during the transitional period. The female has a single elongate ramus tip (Tegelberg and Smith, 2325). Tegelberg and Smith (2325) stated that females taken in October and November could be identified by a distinct blue coloration seen dorsally through the carapace.

At 2 1/2 years the pink shrimp are mature females carrying 1,000 to 3,000 eggs attached to their pleopods. Eggs are present from October through January (Dahlstrom, 2327). The eggs are ellipsoid, 1.2-1.6 millimeters long (2327). At approximately three years of age (2327) spawning of the pink shrimp occurs. There is a seasonal movement to deeper waters (160 fathoms) for spawning (2327; Alverson *et al.*, 2324).

There is disagreement on timing of metamorphosis, spawning, and hatching as shown in the following table.

Time of Spawning	Time of Hatching	Time of Metamorphosis	Reference
Oct-Dec	Feb-Mar		(2326)
Nov-Apr	late Mar-Apr	Early August	(2323)
	Feb-May		(2327)
Mature ova visible under carapace in Aug carried externally by Oct-Nov	Feb-Apr		(2296)

Larval development

Modin and Cox (2295) and Lee (3346) have successfully reared pandalid shrimp in the laboratory. The former found that planktonic larvae were subject to many physical, chemical and biological phenomena in the ocean and that this stage of their life is a very vulnerable one. In both studies egg-bearing shrimp were transported to specially equipped aquariums where temperature was controlled and the water could be filtered, aerated, and ultra-violet treated to reduce bacterial growth. Modin and Cox (2295) maintained a constant water temperature of 10-12°C. Lee (3346) maintained a water temperature of 13°C (±0.2°C) and a pH and salinity of 7.8 and 24.1‰ respectively. Details of development are in both papers.

Magill and Erho (2296) stated that pink shrimp may be particularly susceptible to overfishing since the large shrimp which are most available to the fishery are females. A reduction in the female pink shrimp population could be conceived to be serious, if the female brood stock became low enough to result in a year class failure.

The information on the shrimp seemed to be limited in the sources used. Some studies on thermal and salinity tolerances, food habits and ecology would be helpful.

Other information on the pink shrimp includes:
Fishery - Alverson *et al.*, 2324; Magill and Erho, 2296; Modin and Cox, 2295
Predators - Dahlstrom, 2327.

16. *Sardinops sagax* (Jenyns) (Pacific sardine)

by Nancy Blind

Sardinops sagax is the presently accepted name of the Pacific sardine, but it is also found under *Sardinops caerulea*. It ranges along the Pacific Northwest coast. It has been taken as far north as southern Alaska, off the outer coast of Vancouver Island. It has been found along the Washington, Oregon, and California coasts and its southern range is lower California and the Gulf of California. The sardine is not found more than 550 to 750 km from shore, usually less than 180 km (Clark, 2976).

The Pacific sardine is an inshore, pelagic, south temperate fish. The southernmost end of its range abuts on tropical waters and this boundary seems to be relatively uniform geographically (Murphy, 2982).

Ecology and life cycle and biology

Much of the information concerning the behavior, locations, etc. for spawning sardines seems to be speculative.

Farris (3428) studied the sardine and found that they exhibit diurnal and seasonal periodicity but do not exhibit lunar periodicity.

Spawning

Sardines spawn planktonic eggs under fairly specific temperature conditions. The temperature range for spawning is between 12°C and 17°C (Ahlstrom, 2473) but under lab conditions they have spawned at 13-24°C (Lasker, 2385).

Spawning centers are off Southern California and include Cedros Island, Baja California, and Northern Baja California (Dahlstrom, 2700). Most spawning takes place in April through June but it does occur throughout the year (Ahlstrom, 2473).

The eggs are fertilized after extrusion and float freely in the upper 50 meters of water. After three days the eggs hatch into tiny transparent, thread-like larvae about 3 mm in length. The larvae reach the sandy beaches of Southern and Lower California (Clark, 2976).

Temperature

Lasker (2385) ran some experiments on yolk utilization and found that the energy provided by the yolk would meet the metabolic needs of the animal at 14°C until 160 hours after spawning. From this time on, the larvae were on a continuing energy deficit and were actually at a critical stage in their life. They must be able to feed and food must be available. Lasker (2592) also showed how important the temperature is to the struggling larvae, for functional jaws and pigmented eyes fail to develop in sardine larvae at temperatures below 13°C. Lasker (2592) ran some temperature experiments with anchovies (which seem to be competitive) and found that they hatch sooner and develop normally at these lower temperatures. A two-degree decrease in temperature (from critical temperatures) for the sardine larvae can prolong the rate of development by one-third and larval survival may decrease concomitantly (Lasker, 2592).

Temperature appears to influence both the time of spawning and the length of the spawning season. If an abundant food supply is available and there is a large area for young sardines, then survival chances are good. All this would tend to depend on temperature (Ahlstrom, 2597).

Feeding

Scofield (2591) stated that larval sardines are unable to strain food because their gill rakers do not form on the gill arch until they are about 20 mm long. Young sardines (40 mm long) feed primarily on copepods, and sardines 100 mm long feed primarily on diatoms. Other studies how little variation to this one (Arthur, 3644). Hand and Berner (2593) felt that crustaceans are the most important food source with copepods highest on the list, but they stated that the size of the fish didn't have much to do with the food contained in the stomach. They also stated that the sardine is primarily an omnivorous filter-feeder rather than a particulate feeder.

Lewis (5540) stated after feeding studies in the San Diego area that sardines eat diatoms, dinoflagellates and crustaceans. He felt that fluctuations in temperatures affected the abundance of diatoms which affects sardines. He believed that lower temperatures favoring growth of diatoms attracts sardines.

Salinity

Walford (2594) made some studies on the correlation between fluctuations in abundance of the Pacific sardine and salinity of the sea water; salinity reflecting the intensity of upwelling which increases plankton production. As has been pointed out, an environmental condition most critical to the young sardine is the abundance of food. This varies directly with the availability of nutrient salts which in turn is dependent on strength of upwelling. What is suggested here is that intensity of upwelling or surface salinity is highest in summer, and this is at the same time a critical period in the life of the young sardine, and also a period of maximum solar heating.

A comprehensive review of the life history and biology of the sardine has been compiled by Gates (5649). Investigations on thermal ecology as such are limited to just the spawning temperature ranges and development of the larvae. This report indicates that some information is known concerning lower temperature tolerance but not the effects of elevated temperatures. Knowledge of the early life history of the sardine is incomplete. Ecological studies would also be of value.

Other studies on the sardine include:
Spawning behavior - Wolf, 2619
Fecundity - Clark, 2976
Behavioral studies - Fink, 2861; Yoshimuta and Mitsagi, 2595;
    Clark, 2967; Loukashkin, 2596
Catch statistics - Kimura and Blunt, 2708; Marr, 3641
Parasites - Kunnenkeri, 3645
Morphology and Serology - O'Connell, 3638; Voorman, 2817

17. *Sebastodes alutus* (Gilbert) (Pacific ocean perch)

by Nancy Blind

The genus *Sebastodes*, one of the largest on the northeast Pacific coast, is represented by 52 species in this area. Several of the species are important commercially but probably the one of greatest importance is *Sebastodes alutus*, the Pacific ocean perch (DeLacy *et al.*, 5624). The Pacific ocean perch is found from the Bering Sea to Santa Barbara, California (Clemens and Wilby, 2390), but the fishery is concentrated in the northern parts of its range. Westrheim (5567) reported its depth range as being 38 to 350 fathoms.

Biology

Information on the life history of the Pacific ocean perch is minimal at best. Much recent information has come from Russian studies carried out in the Gulf of Alaska and the Bering Sea. Because data are wanting from the Pacific Northwest populations, some data from the Bering Sea are included herein.

Reproduction

Westrheim (5567) concluded that birth for *S. alutus* occurred in January, February and March. Paraketsov (5752), however, in a study conducted in the Bering Sea, reported that fertilization occurred in January and February and that hatching took place in March through May. It has not yet been determined for this species whether or not the eggs hatch within the ovary or after they have been released (DeLacy *et al.*, 5624).

Distribution and migration

Usually, there is a 1:1 sex ratio in a catch of Sebastodes alutus, but this varies during the year. Westrheim (5567) found that the males seemed to dominate during February and March and that their numbers reached a minimum in September. The lack of females in the population during February and March may be connected with spawning activities. Fadew (5759) found that spawning populations tended to move to shallower waters. According to Lyubimova (5753, 5758), the females form a separate group at this time and move away from the males to the spawning areas. After hatching, which takes place from March to April in the Bering Sea, the females begin to feed intensely and then rejoin the males. The adults are found at a greater depth in the winter in the Bering Sea. Paraketsov (5752) reported that during the winter, the largest aggregations were found at 340-420 meters and in the summer at 140-360 meters. From May to September the adults forage and fatten in open waters (Lyubimova, 5753). Fertilization takes place in November and December according to Lyubimova (5758), but Paraketsov (5752) reports it to be during January to February.

The young ocean perch form separate schools from the adults. The surface temperatures near the Pribilov Islands which are the main spawning grounds in the Bering Sea were around 3.8°C-4.2°C (Paraketsov, 5752). However, temperatures at places of larval shoaling ranged from 4-5°C to 14°C (Lyubimova, 5756).

The young eat planktonic crustaceans during their first two years (Paraketsov, 5752). During their third year of life, they change to a demersal mode of life. The growth rate is high during the first 5 to 6 years (Lyubimova, 5756) and maturity is reached between 6 and 8 years (Paraketsov, 5752).

Westrheim (5567) found that fish in commercial catches ranged in size from 25 to 48 centimeters with the main part of the population occurring between 32 and 44 cm. Males were somewhat smaller than females, and rarely exceeded 40 cm. The females ranged between 32-44 cm. Paraketsov (5752) reported for the Bering Sea that the average length for males was 46 cm and for females, 49 cm. The maximum size for S. alutus according to Lyubimova (5758) is 40 cm and 1.5 kg. The maximum age seems to be around 25 years with the 14 to 16+ age groups dominating the catches (Gritsenko, 5754). This figure was given as 11-18 year class by Paraketsov (5752).

Feeding

The adult Pacific ocean perch feed in open waters mainly on euphausiids, calanoids, hyperiids, mysids, amphipods (Paraketsov, 5752). Sebastodes alutus seems to be important as food for halibut and albacore (Clemens and Wilby, 2390).

No extensive migrations have been indicated for S. alutus except those connected with spawning activities (Fadew, 5759). However, the populations in the eastern and western portions of the Pacific are considered to be of the same biological stock with differences in local populations (Lyubimova, 5756, 5758).

Additional information which is available:
Fecundity - Westrheim, 5567
Catch statistics - Niska, 5853; Westrheim, 5567; Alverson et al., 5735; Greenwood, 5751.

18. Siliqua patula Dixon (Pacific razor clam)

by Danil R. Hancock

The Pacific razor clam Siliqua patula Dixon is a most important molluscan species in the Pacific Northwest. Its total value is more than that of all other molluscs in the state of Washington (McMillin, 2732). Although it ranges from the Aleutian Islands in Alaska to Pismo Beach, California (Anonymous, 3597; Fitch, 2227), its distribution within these limits is far from ubiquitous. Broad flat beaches of fine sands retaining interstitial water are most typical but it exhibits preference for ocean beaches where a strong surf beats constantly and appears to be dependent on wave action for carrying out its life activities. Although sometimes found on the inland side of spits, it will not grow in sheltered bays (McMillin, 2732).

Maximum abundance of young and old occurs at about 30 cm below mean low water. Large clams are usually found about 30 cm under the sand and smaller clams nearer the surface. According to McMillin (2732), 350-550 m from low water line is the lower limit of the razor clam, and the beds are limited in width to the area near mean low water. Diving observations have indicated at least a fair population of clams exists 1 km offshore but Tegelberg, Magoon, and Woelke (personal communications) further stated that the offshore distribution of the razor clam has never been established, and that a separate offshore population may exist.

Locomotion in razor clams is by means of digging with the large muscular foot. The digging actions are so rapid that a large clam can be buried in 1/2 to 2 minutes and a young clam can bury itself in 5-10 seconds. Clams have been reported several feet beneath the surface. Such locomotion provides protection from shifting sands and predation from enemies (McMillin, 2732). Larger members of a year class were found lower than smaller members, however this comparison did not include offshore areas (Hirschhorn, 3816). Razor clams orient to the direction of wave action, with the hinged side toward the ocean.

The region of the Washington coast just north of the Columbia River and extending to the Quinalt Reservation appears to be a region of maximum density and supports the largest fishery. Densities here have been recorded as high as 12,000/m^2 (1450 clams/square foot) at Copalis Beach in August, 1923 (McMillin, 2732; Tegelberg and Magoon, 3407). In Oregon, Clatsop county beaches are the region of maximum abundance of the razor clams. These beaches have supported a commercial and recreational fishery for many years under a commercial minimum size limit of 3.5 inches (90 mm) and a sport fisheries bag limit of 36 clams.* In the period 1955-1962 the Clatsop beaches yielded one million razor clams to the sport fishery and 308,000 to the commercial fisheries (Anon. , 3597). Until about 1914 many productive razor clam beds were known along the entire coast of Oregon, but many of these have disappeared. In 1920 Edmondson (2345) wrote, "Until about six years ago beds of razor clams of considerable size were known to exist at many points throughout the entire coast of Oregon. There apparently occurred, however, a sudden depletion of the species along the sandy beaches south of Tillamook Head, a satisfactory cause for which has not been ascertained."

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*Current Oregon limit 24 clams/day, no size limit.

Spawning

Sexes are separate in the razor clam. The mature female (age two years) produces six to ten million eggs. The rich, yellow, "ripe" ovaries contribute 30% of the animal's non-shell weight. Ovarian follicles, each containing 100-150 eggs, rupture releasing eggs through the siphon into the water. Both eggs and sperm are released when the water temperature reaches 13°C and fertilization occurs in the water. The clams on one section of the beach spawn simultaneously, and the triggering of this is thought to be due to the release of certain chemical substances into the environment. Washburn (3609) indicated the bulk of spawning occurred during April and May. McMillin (2732) indicates the principal spawning period was between May 15 and June 5 but noted that a very small amount of spawn is released in October. On Clatsop beaches (Anon., 3597) spawning occurs in late spring and summer with almost 98% of the spawn cast out in 2-4 days. Dispersal of eggs is determined by the currents and waves and is thought to be limited. The fertilized egg is "pear shaped" with a white spot in the center. After subsequent cleavage (about 3 weeks) the fertilized eggs become a veliger larvae and begin swimming. The number of weeks before the free living larvae "sets" or begins to dig into the sand varies from 5 to 8 weeks (Fulton, 3600; McMillin, 2732; Anon., 3597). The veliger larvae are distributed by currents and waves during the larval stages and migration of adults is very limited (McMillin, 2732). Because of small size, the young set are unable to withdraw rapidly from the top layers of sand and hence their movement is likely to be governed by upper sand layers. During erosional phase of the annual beach cycle upper layers of sand move offshore and are a ready vehicle for the redistribution of small razor clams (Hirschhorn, 3816). The spawn develop in water ranging in temperature from 11-17°C.

Mortality of larvae and young razor clams can be very high. McMillin (2732) records 99% loss from fall 1923 to mid February 1924, and Tegelberg and Magoon (3407) observed a 95% mortality of set during a severe storm. Mortality of young is influenced by such things as freshwater runoff (rain) crowding, predation, and sediment disturbances. Natural predators are sea gulls, ducks and fish. Man-caused mortalities of young are alteration of clam beds by coastal construction (groins, jetties, outfalls), vehicular traffic on clam beds, and careless digging.

After reaching sufficient size to actively dig, the mortality rate is greatly reduced and life spans of 15 years have been recorded in Alaska. At the southern end of the range the average life span is four years, and the maximum life span on Copalis Beach, Washington, is about 8 years (Anon. , 3597).

Food and feeding

The razor clam is a filter feeder. Water containing diatoms, organic detritus, and some small animals is taken into the mantle cavity by the inhalent siphon. As the water passes over the gills food is taken out and passed to the stomach (McMillin, 2732). Tegelberg and Magoon (3704) feel that the major food source of the razor clam is the diatom *Chaetoceros armatus*, and that growth rate is dependent on food supply. They conclude the poor growth in the 1966 set of clams on Washington clam beaches was due to overpopulation which caused a drastic reduction of the plankton supply. Growth is thought to be proportional to food intake while temperature of the water influences the intensity of feeding (McMillin, 2732). Relative shell width was found to increase during the period March-July, as did maximum increase of total length. Size increase appears to be associated with seasonal rises in water temperature (Hirschhorn, 3816).

Temperature

Temperature of the water is thought to play an important role in spawning, feeding, and growth of the razor clam, yet there appears to be little evidence for such thinking. In fact, very little is known about either the thermal tolerances or the responses of this clam to temperature. Some very preliminary temperature tolerance tests on adult razor clams indicated that a two-hour exposure to 75°F (24°C) was lethal (Tegelberg, personal communication). Larval razor clams are expected to have a narrower temperature tolerance than the adults (Fulton, 3600).

Ova are found in female clams throughout the entire year; therefore if increased temperatures or changes in temperature play a role in spawning, the effects of a lens of warm water from a thermal outfall could be significant. Since the razor clam moves very little after settling, such a warming of the water may cause spawning at times that are not optimal. Growth parameters of the Pacific razor clam are quantitatively associated with mean annual air temperature at localities ranging from California to Alaska (Taylor, 3831).

19. Thaleichthys pacificus (Richardson)
(Columbia River smelt, eulachon)

by Nancy Blind

The eulachon is an anadromous member of the family Osmeridae. Until fairly recently its range was thought to extend from the Bering Sea to the Klamath River in California, but records show that it has been found as far south as Bodega Head, California (Odemar, 5804).

Since spawning and the hatching of the larvae takes place in freshwater from mid-March to mid-May, they will not be treated in any detail here. "Little is known about the distribution of eulachon from the time the larvae leave the river until the time the adults return to spawn" (Barraclough, 5798). The eulachon spend two years in the ocean and return to the rivers to spawn at three years. The larvae and juveniles are prevalent in the echo-scattering layers. The stomachs of those caught were full of euphausiids (Barraclough, 5798). The adults also seem to be plankton feeders; Cumacea dawsoni is the only species positively identified from stomach contents (Smith, 5795).

The eulachon may be an important link in the food chain as it is consumed by a number of different species, among which are sturgeon, halibut, cod, porpoise, finback whale, seals and sea lions (Hart and McHugh, 5538). Adults have also been found in the stomachs of the dogfish, salmon, hake, lingcod, harbour and fur seals but its relative importance in these diets is unknown (Barraclough, 5798). They also may be important in the food supply of Cancer magister as well as other shore species (Smith, 5798).

Fishermen have reported large aggregations of eulachon off the mouth of the Columbia River in November, December and January, just prior to their move up river. Migration upstream may be influenced by temperature of the river water (Smith, 5795).

The fish are primarily caught as they go up river to spawn. Males seem to predominate in the commercial catch (Smith, 5795). Most of the spawning fish die but some may survive and return to spawn again in their fourth year (Barraclough, 5798).

For catch data on the Columbia River smelt see U. S. Fish and Wildlife Service Statistical Digest for years of interest.
Spawning - Hart and McHugh, 5538; Smith, 5795; Barracough, 5798.

20. Trachurus symmetricus (Ayres) (Jack mackerel)

by Nancy Blind

The range of the jack mackerel extends from the Gulf of Alaska to Cape San Lucas, but the fishery is concentrated in Southern California, from Monterey to San Diego (Ahlstrom, 5748; Anon., 5729). Adults have been taken 1100 km from shore and the eggs and larvae have been taken as far seaward as 2000 km off the coast of Washington (Ahlstrom, 5748). Studies indicate that there is one population along the Pacific coast (Roedel, 5746).

Spawning takes place primarily from February to October (Farris, 5619) with the peak ranging from April to June (Ahlstrom, 5724). Cruises along the California coast produced the following results: 1951--the peak number of eggs occurred in March, 1952--spawning began in January with the peak in May and ended at the end of September, 1953--spawning began in February with the peak in April, 1954--the peak occurred in May (Farris, 5747).

Spawning is pelagic and takes place (Ahlstrom, 5724) mainly from 150 to 450 km offshore (MacGregor, 5741). Larvae have been taken as far north as Washington (Anon., 5729; MacGregor, 5741) but the area of concentration seems to be from Point Conception, California, to San Quentin, Baja California (Anon., 5729). The jack mackerel lives in the upper water layers, between 16 and 90 m (Ahlstrom, 5724). In one survey, 97% of the eggs and 88% of the larvae were taken in the upper 50 meters (MacGregor, 5741).

Very little is known about the mating activities of the mackerel but evidence indicates that most spawning occurs around midnight (MacGregor, 5741). Indications are that females spawn more than once in a season (Anon., 5729).

Temperature of the water has a definite effect upon the incubation time. It has been shown that hatching occurs in 108.5 hours at 14°C and 84 hours (3.5 days) at 15°C. Temperature may also have importance in relation to where the jack mackerel spawns. The spawning area is approximately bounded by the 26th parallel in the south, the 45th parallel in the north and the 150th meridian on the west. Within the southern California area, and at a depth around 10 meters, where the greatest abundance of eggs occurs, the temperature remains fairly constant around 15.5°C. In one study, it was found that 60% of the spawning took place within 1° of 15.5°C (Farris, 5619). Another survey indicated that 70% of the larvae collected were in waters of 14-16°C (MacGregor, 5741). However, despite the constancy of temperature in the California area, spawning occurs only in the spring and summer. Therefore, it is thought that photoperiod may also be of some importance (Farris, 5619).

At hatching, the larval jack mackerel is somewhat larger than the larvae of either the anchovy or the sardine. However, it has no eyes, fins or mouth (Ahlstrom, 5724). After the development of these features, the larvae feed upon minute crustaceans (MacGregor, 5741). Microsetella norvegica seems to be particularly important (Ahlstrom, 5724). At this stage the jack mackerel eats nearly the same things as do the anchovy and sardine but the specimens it can consume are somewhat larger than those taken by the other species. This is probably one of the reasons for its success (Ahlstrom, 5724). Survival at the end of 30 days after hatching was calculated as 131, 112, and 179 larvae per 100,000 eggs hatched for the years 1952, 1953, and 1954. The variation was considered insignificant (Farris, 5619).

Very little is known about the juvenile stage except that juveniles eat euphausiids, pteropods and copepods. Copepods seem to be more important to the juveniles than to the adults (MacGregor, 5741). The jack mackerel matures between the second and third year (Anon., 5729).

Predation by organisms other than man has not been studied (MacGregor, 5741) but it is assumed that the jack mackerel is consumed by sea lions, porpoises and most of the large predatory fish in the area (Anon., 5729). The Pacific mackerel is considered its most important competitor (MacGregor, 5741).

Feeding

The adult jack mackerel is known to eat euphausiids, copepods, pteropods, anchovies, lanternfish and juvenile squid (Anon. , 5729). The fish have been observed feeding on saury and lanternfish gathered beneath the floodlights of a ship at night. The jack mackerel congregated 3 to 5 meters below the surface in schools of around forty fish. They selected and chased individual prey (Grinols and Gill, 5742). Mackerel seem to feed at any time during the day but it is not known if they feed at night (MacGregor, 5741).

Schooling and migration

The jack mackerel is a schooling fish and there has been some research regarding the effects of light on feeding and schooling and the organization of the schools before, during and after feeding. Schooling seems to be determined by size. It was observed in one laboratory study that schools of juveniles that were rather disperse during feeding became more compact after feeding (Hunter, 5745).

Not much is known about migrations of the jack mackerel (MacGregor, 5741). In 1950, adult jack mackerel taken at a depth of 20 meters were found in temperatures ranging from 10°C to 19. 5°C (MacGregor, 5741).

Other information on the jack mackerel includes:
Catch statistics - U. S. Fish and Wildlife Service, Statistical Digest, No. 55-60. Information available for California only.
Growth, maturation and life span - MacGregor, 5741; Roedel, 5746; Anonymous, 5729
Fecundity and egg description - Anonymous, 5729; Ahlstrom, 5724; MacGregor, 5741
Behavior - Hunter, 5744

PART IV - INTEGRATED ECOLOGY

Chapter 21. THE NEARSHORE COASTAL ECOSYSTEM: AN OVERVIEW by James E. McCauley, William C. Renfro, Robert H. Bourke, Danil R. Hancock and Stephen W. Hager

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Chapter 21. THE NEARSHORE COASTAL ECOSYSTEM: AN OVERVIEW

by James E. McCauley, William C. Renfro,
Robert H. Bourke, Danil R. Hancock and Stephen W. Hager

An ecosystem is defined as "any area of nature that includes living organisms and nonliving substances interacting to produce an exchange of materials between the living and nonliving parts," (Odum, 1959). This broad concept can be used to advantage in considering an area subject to possible pollution. Knowledge of the various living and nonliving components in sufficient detail to understand their interrelationships enhances our ability to anticipate changes resulting from pollution of the ecosystem. In one sense, pollutants, such as toxic chemicals or heated water, might be thought of as additional environmental factors which might alter the system drastically. Patently, a certain minimal level of information is necessary for even crude predictions of the effects of pollution.

No ecosystem is a completely self-contained unit, and the Pacific Northwest coastal region is no exception. It is influenced by adjoining regions such as the open Pacific Ocean to the west and the land mass to the east. These adjacent regions have a marked influence on the climate and are the sources of many inputs into the system. Although we can look at the region as a somewhat discrete unit, we must continually keep in mind the influence of these contiguous territories. Within the coastal ecosystem there are many interrelated physical, chemical, geological, and biological processes. In the following section an attempt will be made to describe some of these important factors and the manner in which they interact.

The area considered here is the coastline of the Pacific Northwest, extending from Cape Flattery, Washington to Cape Mendocino, California. It can be characterized as a series of sandy beaches interspersed with rocky headlands. This coastline is oriented in a north-south direction and, except for local headlands and bays, is nearly straight. The absence of major embayments and irregularities results in a smaller variety of habitats than would normally be expected to occur on a more highly dissected coastline. A large portion of the coastline is, therefore, subjected to the full impact of breaking waves.

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The sandy beaches generally lie at the foot of low bluffs which are usually not more than 10 meters high. Occasionally the bluffs reach much greater heights, especially along the southern Oregon coast. In some areas the bluffs may be greatly reduced as along the Clatsop Plains region of northern Oregon or along the spit that separates Willapa Bay from the ocean near Long Beach, Washington. In other regions the bluffs may be far inshore, separated from the beach by extensive sand dunes as occurs near Florence, Oregon.

The beaches are composed primarily of quartz and feldspar that have been derived from ancient marine terrace deposits found along the entire length of the inner continental shelf off Washington and Oregon. These beach sands are conspicuously lacking in shells and shell fragments which characterize the beaches of the mid-Atlantic states.

Beach profiles exhibit wide annual fluctuations in response to wind-generated wave conditions, being broader and steeper in summer. The intertidal microfauna of the sandy beaches of the Pacific Northwest has not been extensively studied. The macrofauna is limited to a few species which are mostly burrowing organisms. The well-sorted character and large particle size of these beaches, combined with a low content of organic matter, results in low species diversity. Particle size of the sand also affects the compaction and aeration of the beach, thereby affecting its suitability as a habitat for animals which burrow into it or obtain nourishment from it. The shifting of the sand and the absence of rocks or cobbles generally exclude macroalgae from the sandy beaches of the Pacific Northwest. In northern Oregon and southern Washington sandy beaches harbor vast numbers of razor clams, Siliqua patula, but no other intertidal species are of great economic importance.

Basaltic headlands alternating with the sandy beaches provide rocky intertidal areas having an exceedingly rich flora and fauna. In some areas, offshore rocks and reefs temper the force of the surf on these headlands forming the well-known protected rocky outer coastal habitat. This type of environment, considered to be one of the most productive, is a graphic example of the moderating effect of the geomorphology on physical oceanographic processes which, in turn, profoundly influence the biology. Tides, with an average range of about two meters, bare much of this area at low tide, subjecting it to abnormally high temperatures. The degree to which the exposed intertidal surfaces are heated by absorption of short wave solar radiation is largely determined by the nature of the substrate. Dark surfaces absorb greater amounts of energy than lighter ones. Hence, organisms found on dark surfaces may tolerate, or even require, broader daily ranges of temperature and higher temperatures than those on lighter surfaces. Such subtle differences in substrate characteristics may have significant effects on the composition and distribution of intertidal communities.

The water level changes due to tides have a marked effect on the distribution of intertidal species. Vertical zonation is generally quite evident, especially on the more vertical rock faces. The California mussel, Mytilus californianus, the ocean goose barnacle, Pollicipes polymerus, and the sea star, Pisaster ochraceous, constitute a trio of species which form massive beds in the upper intertidal zone. The splash zone above has its own biota, consisting primarily of smaller species. The zones below also have characteristic plants and animals and generally have a great number of species. The Mytilus-Pollicipes-Pisaster zone is alternately exposed to air and water and the upper limit of this zone is generally determined by this exposure. The lower limit, however, is most likely controlled by predation of the starfish on the other two species. This illustrates the interaction of biological and physical influences on the distribution of species.

The intertidal community is dually exposed to predation. When covered with water, fishes, seals, diving birds and other marine species have ready access to the organisms. At low tides, shore birds and terrestrial animals invade the region. Man, too, has become a major influence on the ecology of intertidal zone along the Pacific Northwest coast. The impact of intertidal collectors (tourists, school and college classes) and fishermen has become so great that use of the region must be regulated to protect the species. In many areas Pisaster ochraceous, the starfish that was once a most conspicuous part of the fauna, is now a rare species, having been removed by human visitors to the beach. How will man's predation on Pisaster effect the Mytilus-Pollicipes-Pisaster zone of animals? Will Mytilus and Pollicipes encroach upon the lower zones?

Man-made structures have altered the shape of the coastline and provided solid substrates for the attachment of many sessile organisms. Jetties have been constructed to protect practically all the harbor entrances along the Pacific Northwest coast. These jetties disrupt the movement of sand along the coast. The seasonality of this alongshore movement, or littoral drift, causes sandy beaches to build up on both north and south sides of some jetties. Breakwaters and groins similarly alter the natural flow of sand in the littoral drift.

The nearshore subtidal area is largely composed of sands similar to those found intertidally, but become finer farther from shore. The sand characteristically has a median diameter ranging from 200 to 300 microns and makes up nearly 100% of the sediment. The supply of sand to this area from coastal rivers is small, most of it being trapped in the estuaries of the supplying streams. Silt and clay sized particles, however, are supplied to the nearshore region in significant quantities. These particles do not settle, but remain suspended and are transported from the area, most being deposited farther out on the continental shelf. This suspended material may be important in removing toxic substances from the water. For example, toxic organic substances, such as pesticides or pulp mill wastes, and toxic trace metals (e.g., mercury, lead, etc.) may be absorbed or adsorbed by the suspended silt and clay particles and be deposited farther offshore.

The subtidal region has a moderate slope of about 1 : 80 such that at one kilometer from shore the average depth is about 10-14 meters. In the northern part of the area under consideration the slope is somewhat less than this; in the southern part, somewhat more. Gravelly or rocky substrates are found off the mouths of many coastal rivers due to the scouring action of the more intense tidal currents created by the flow of water entering and leaving the estuary. Rocky outcroppings occur off most headlands either as sea stacks which have resisted erosion or as rubble which has fallen from eroding headlands. Sea stacks are common off the major headlands such as Tillamook Head, Cape Arago, and others, and are a dominant part of the seascape within several kilometers of the shore south of Cape Blanco. These structures may have a large influence on the local, nearshore circulation (to be discussed later) which, in turn, may affect communities by altering the transport of nutrients, pollutants, and pelagic larvae.

Two dynamic communities interact in this nearshore subtidal region: (1) A benthic community consisting of those organisms living in or on the sediment or near the sediment-water interface and (2) A pelagic community consisting of those organisms drifting, floating, or swimming in the overlying water. Because of their interactions, the boundaries of these communities are not clear. The Pacific herring, for example, deposits eggs which become part of the benthic community while the larvae and adults are members of the pelagic community. Conversely, many of the benthic species produce eggs which float to the surface, hatch into planktonic larvae, and become dispersed by ocean currents before settling permanently to the bottom. In many other cases, benthic fishes swim up into the surface waters to feed on pelagic organisms, while such pelagic species as sea otters dive to the bottom to feed on benthic sea urchins. The benthic community depends upon the continual "rain" of materials from the overlying waters in the form of decomposing organisms, fecal pellets, suspended sediment particles, etc., for nourishment. These bottom organisms, including bacteria, marine worms, etc., perform the valuable function of breaking down these organic materials into elemental forms which are recycled. The cycling of some elements have been studied by following radionuclides artificially induced in the Columbia River at Hanford, Washington, and subsequently incorporated into the marine biogeochemical system.

This nearshore subtidal region with its many interacting communities is the site of several major fisheries in the Pacific Northwest. The largest of these is the salmon fishery, but Dungeness crab, shrimp, perch, sole, founder, bass, and rockfish fisheries contribute significantly to the economy of the region.

The temperature of the nearshore coastal surface water varies seasonally, ranging from an average high of 17.7°C to an average low of 7.6°C. The annual range in mean temperature is small, however, with mean summer temperatures (14°C) being about 5°C warmer than mean winter temperatures (9°C). Such a small annual temperature range is in sharp contrast to that of many other coastal regions. More variability is observed in summer than in winter. Summer temperatures fluctuate within a 4 to 6°C range while winter temperatures are constrained to a 1 to 2°C range. Due to the warming influence of the Columbia River, summer temperatures are 2 to 3°C higher in the vicinity of the river mouth (from Willapa Bay to Tillamook Head).

Coastal upwelling, most prevalent off southern Oregon and northern California, tends to suppress the high surface temperature normally expected during summer. Average temperatures of 9.5 to 10.5°C are observed in regions of active upwelling. At the same time, temperatures of 12 to 14°C are found in nearby regions undergoing little or no upwelling.

The net heat exchange across the air-sea boundary varies from year to year due mainly to fluctuations in solar radiation and evaporation. Seasonal fluctuations of these two factors also establish an annual cycle of net heat transfer. From April through September the ocean is warmed by a transfer of heat from the atmosphere to the oceans; October through March constitutes a cooling period when the ocean gives up heat to the atmosphere. Net solar radiation reaches its maximum during the summer months. The insolation during April through September is more than twice that received during the winter months. Heat loss due to evaporation is at a maximum during the winter months. The evaporative process is supressed during the summer months when upwelling is prevalent.

Atmospheric temperatures observed at coastal weather stations and at lightships range from a mean summer temperature of approximately 14°C peaking in August to a mean winter temperature of approximately 10°C during January through March.

Average surface salinities are higher in summer than in winter (approximately 33.5‰ and 32‰, respectively). Coastal upwelling tends to keep salinities high during the summer, while winter rains and high river run-off tend to lower surface salinities. Where coastal upwelling is prevalent, salinities are frequently observed in excess of 33.8‰ but seldom exceeding 34.4‰. In winter the discharge from the Columbia River flows northward along the Washington coastline. Mean salinities observed along the southern Washington coast are low (25 to 28‰) with maximum salinities rarely exceeding 30‰. In June, during periods of peak river flow, salinities less than 20‰ have been observed from Seaside, Oregon to Willapa Bay, Washington.

The quality of sea water depends not only upon those substances which are a natural part of the marine ecosystem, but also upon those substances which have been added by man. Little is known about the natural properties of Pacific Northwest nearshore coastal waters except for those tied closely to biological production and upwelling. These properties, pH, dissolved CO_2, inorganic nutrients, and dissolved oxygen,are discussed later under considerations of upwelling.

Substances introduced into the nearshore waters of the Pacific Northwest by man include domestic sewage, pesticides, and pulp mill effluents. The interactions of these substances with the environment have not been studied thoroughly in this region. Although there are four pulp mill outfalls in this coastal zone, little is known about the interactions of these waste products with sea water and nearshore communities.

One feature of the Pacific Northwest coast which sets it apart from the more southerly coasts is the occurrence of much driftwood washed ashore or water-logged in the sub-tidal area. This wood, carried to the oceans from logging activities ashore or lost from log-rafts at sea, provides a substrate for those communities which attach to floating objects or bore into submerged wood. In the surf these logs are a hazard to swimmers and boaters and may act as battering-rams dislodging attached animals and damaging sea walls.

The trend of the winds over this coastal area is largely influenced by the barriers presented by the coastal bluffs and nearby mountains. Summer winds prevail from the northwest (WNW in the northern region, NNW in the southern). Winds observed at the lightships off Cape Flattery, Cape Mendocino, and the mouth of the Columbia River are similar to those observed at coastal stations suggesting that the influence of the coastal bluffs and mountains is felt at least 10 kilometers offshore. Most winter storms are southwesterly, but prevailing winds during the winter generally have an easterly component. The net result of these wind forces is a seasonal pattern of nearshore water movement either northward or southward along the coast.

Littoral sand transport along the coast is responsive to the local wind-generated wave action and moves sand northward during the winter and southward during the summer. The more severe winter storms generate higher waves tending to make the annual net movement northward, but this may vary locally. Except for seasonal changes in the beach slope very near to shore, the onshore-offshore movement is negligible. This absence of net offshore transport, combined with reduced net alongshore drift due to seasonal reversals, results in a low rate of removal of sands from a given area. Dispersion of pollutants adsorbed on the sand particles would also be limited by this containment or anti-dispersal mechanism.

The northerly summer winds are also associated with coastal upwelling which brings cold, nutrient-rich waters to the surface to replace the surface water which has been transported offshore by the combined influence of wind stress and the Earth's rotation. Upwelling is particularly apparent in the southern half of the region (southward of Tillamook Head) and generally is initiated in June, becoming most intense in July and August and persisting until September. Periods of subsidence occur during periods of calm or when the wind shifts from the north. The upwelling phenomenon is manifested as local pockets of relatively cool saline water varying locally in intensity. The temperature of this upwelled water is about 11 to 13°C, approximately 5 to 7°C less than that of surface waters 40 kilometers farther offshore. Upwelling has a marked effect on the coastal climate producing local fog and chilly weather during the summer months. Recent studies indicate that upwelling is more persistent in the vicinity of rocky headlands.

Upwelling is an important mechanism for bringing cold, nutrient-rich, low oxygen water to the surface where it can be utilized by phytoplankton. The rich supply of these nutrients, which often limit photosynthetic production, stimulates the growth of phytoplankton resulting in a population explosion or "bloom." Such blooms generally occur between May and September along the Pacific Northwest coast. These blooms are closely followed by an increase in the population of zooplankton which feed on the phytoplankton. The region is thus rich in food for higher trophic levels. Important forage fish, such as anchovy and herring feed on this rich food and in turn are fed upon by salmon and other commercial species. Thus, the success and timing of the fisheries in the Pacific Northwest is closely correlated with the timing and location of intense upwelling zones.

In addition to its higher nutrient concentration, upwelled waters differ from surface waters in other chemical characteristics. Values of pH may be as low as 7.7 or roughly twice as acidic as surface waters (pH 8.1). Dissolved carbon dioxide may reach levels of 500 ppm or more while the level of typical surface waters is generally less than 320 ppm. Oxygen values may be as low as 1.5 ml/l (N. T. P.) whereas usual surface values are about 7 ml/l. Higher concentrations of trace metals probably occur in upwelled waters, and concentrations of dissolved organics and particulate matter may also be high. The implications of these significant changes in chemical composition are not yet fully understood, but they may be as important as the nutrients to the biological systems.

Wave studies indicate that the predominant offshore swell is from the northwest throughout the year. Thus, communities on the exposed northern sides of headlands may differ in their species composition from those on the more protected southern sides. The average height of the swell is less in summer than in winter (1 m and 1.6 m); the average period during both seasons is about 10.5 seconds. Waves generated by local storms are superimposed on this general swell pattern. These locally generated waves are higher (1.1 m in summer, 2.5 m in winter) and of a shorter period (6.4 sec in summer, 8.1 sec in winter) than the swell. Wave height and wave length determine the depth at which bottom material can be resuspended or moved. The resultant turbidity and movement of material may significantly influence the bottom topography, benthic communities, and chemical characteristics of the area. Upon reaching the nearshore area the waves appear mostly as swell and are bent from their direction of approach to arrive with their wave crests nearly parallel to the shoreline. Where troughs, canyons, or other depressions occur on the sea floor, there are regions of divergence where the wave heights are diminished. Off headlands, reefs, bars, and other shoaling areas (regions of convergence), wave heights are increased, in some cases to a height where breakers occur.

Turbulent mixing by the large storm waves of winter causes thorough mixing of the water column from surface to bottom. The small temperature differences observed between surface and bottom waters (about 1 °C) during the summer are absent during the period from December through March or April.

Reliable estimates of wind-driven current velocities beyond the surf zone are not available at present, but observations 5 to 15 kilometers offshore show a general southward surface flow of 20 to 40 cm/sec during the summer. Depending on the strength of the surface flow, a subsurface northward flow may also be present near the base of the permanent pycnocline. It seems doubtful that such subsurface flow would be observed because of the influence of the shallower water and other coastal features. In winter the direction of the southward current is reversed in response to the seasonal shift of the winds. The conformation of the coastline (headlands, reefs, etc.) has a marked influence on local circulation patterns, creating complex eddies, most of which have not yet been studied. Local circulation constitutes the main mechanism for the dispersal of material added to the nearshore area by rivers, erosion, and human activities.

These circulation patterns are also of great importance in transporting planktonic organisms, particularly the planktonic larvae of benthic plants and animals. Such offspring must be transported to a suitable area during proper seasons in order to insure continued maintenance of benthic communities. Distribution of materials such as nutrients, trace metals, and pollutants are also influenced by the currents. Disruption of the usual patterns of longshore water movement during prolonged stormy periods may seriously affect planktonic organisms. Currents also carry foods and other substances to various organisms, especially those which are attached to the substrate, and may also remove waste products which might become toxic if allowed to remain in the area.

A number of rivers empty into the region, including coastal streams and the Columbia River. The impact of the coastal streams is slight compared to that of the mighty Columbia. These rivers introduce fresh water with its load of sediment and diverse chemicals into the ocean. Such riverborne chemicals as trace elements, organic compounds, inorganic nutrients, and particulate matter, may have a great influence on the ecology of the nearshore region. The specific chemical characteristics of each stream are largely determined by the nature of its drainage basin. The chemistry of Pacific Northwest coastal streams is thus influenced by the geology of the Coast Range; the markedly seasonal precipitation patterns; and the activities of various industries, in particular, the forest products industries. The generally low population density in these drainage basins has helped to preserve the pristine quality of the water.

The effects of the coastal streams are generally local and seasonal with discharges ranging from 3 to 30 m^3/sec in summer and 300 to 600 m^3/sec cfs in winter. The Columbia River, however, is much larger (7500 m^3/sec mean annual flow) and has a plume that can be detected far at sea. Its impact on the coastal area is primarily along the Washington coast where the winter plume flows northward close to shore. The summer plume of the Columbia flows southwest from the mouth of the river and is soon far offshore. The influence of the Columbia is not entirely absent from the coastal region of Oregon, however, for traces of radionuclides induced in the Columbia River at the Hanford Atomic Works can be detected in the coastal fauna and sediments at least 300 kilometers south of the river mouth.

The influence of the river on the biota is not always obvious, but anadromous fishes such as salmon, bay smelt, and herring require varying degrees of fresh water for spawning. It is also thought that the chemical make-up of the rivers is important for the successful navigation of these anadromous species, serving as a sort of "fingerprint" to identify the natal stream. Changes of the chemical make-up of a river can hinder their upstream navigation.

Most of the coastal rivers and the Columbia River enter the ocean through well-developed estuaries. Estuaries are the sites of most of the cities and smaller communities along the coast, and also the location of most of the industry. These estuaries have a fauna and flora that are more or less typical of the habitat, and are important feeding grounds for the larvae and juveniles of many marine species. Estuaries undoubtedly have an important impact on the outer coastal zone, but they have been excluded from this study.

In summary, the general uniformity of this coastal region should be emphasized. The plant and animal composition of the entire region shows a remarkable similarity from north to south. Most of the more common species reported from northern Washington have also been reported from northern California and vice versa. There are no major faunal or floral boundaries in the region, and the differences in biota that can be seen between the extremes of the region generally occur gradually. The general ecological factors which are thought to control biological distributions (e.g. temperature, substrate, salinity) all show a relative uniformity throughout the region so that the absence of a biological boundary is not surprising.

In this chapter we have attempted to describe the nearshore coastal region of the Pacific Northwest, to show that it is a dynamic ecosystem interacting with adjacent ecosystems. We have tried to discuss the various components of this ecosystem as they interact and to show that there is great interdependence among these components. In the preceding chapters and in the appendices to this report we have brought together all the information that we could locate about the area. It was necessary for this information to be compartmentalized, although from the ecological viewpoint it cannot realistically be separated into discrete parts. Much of the information is so fragmentary and so incompletely understood that we cannot incorporate it into a large interacting whole. Ecology has not yet reached the degree of sophistication necessary for us to completely understand the complex and subtle interactions within an ecosystem, but it is probable that any available information may be useful and perhaps even essential.

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